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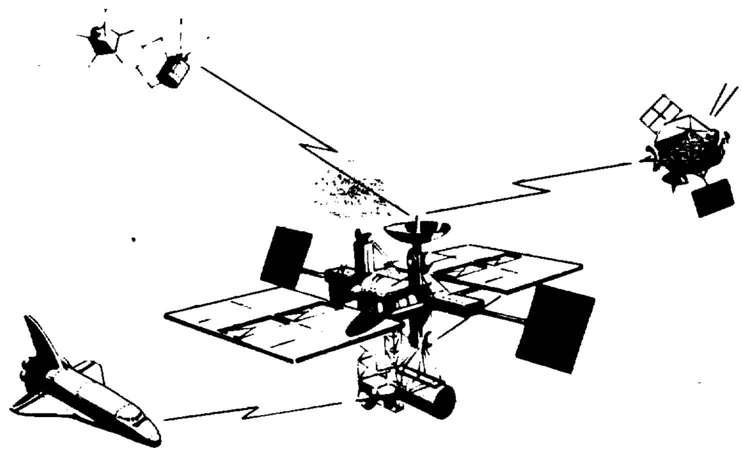

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JPL

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

FOREWORD

This document describes a candidate functional architecture concept for an autonomous command and control system and discusses technologies associated with autonomous control in general and the concept in particular. The core space station component of the NASA Space Station System serves as the focus of the example, though the basic concept of a functional control hierarchy is applicable to control of any complex spacecraft system.

The technology needs described in the appendix were derived prior to the development of the command and control architecture concept. The technology assessment of the NASA OAST Programs and Specific Objectives (PASO) document is related to details of the example command and control architecture. The recommendations of the assessment, however, are applicable to autonomous control in general and are not architecture specific.

The autonomous control functions for the example space station core concentrate on the primary service functions needed for the core and payload users. Not all subsystem areas and applications are addressed. The Environmental Control and Life Support Subsystem (ECLSS) is not addressed in this effort. Thermal control, propulsion, telecommunications, and robotics were considered in the technology needs (Appendix A) phase but are not addressed specifically in the example of the architecture concept. Specialized applications of robotics and teleoperations for specific missions such as the Orbital Maneuvering Vehicle (OMV) and Orbit Transfer Vehicle (OTV) are also not addressed.

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EXECUTIVE SUMMARY

During fiscal year 1983, JPL's Autonomous Spacecraft Systems Technology (ASST) team has been (1) assessing space station needs for new technology in the field of autonomous systems, (2) evaluating autonomy technology needs with respect to the technology-development program of the Office of Aeronautics and Space Technology (OAST), and (3) preparing recommendations for improving the alignment of the OAST program with space station autonomy needs. This document reports the FY'83 results. The report consists of three parts:

Part 1 describes the objectives of the ASST task and the methods used.

Part 2 presents a candidate functional architecture for autonomous command and control of the space station and identifies the generic technology needs that are inherent in the architecture.

Part 3 relates the technology needs identified in Part 2 to OAST's FY'84 PASO tasks. For some needs, no PASO task currently exists; in such cases, a new PASO task is formulated for future support. For each current task, Part 3 makes recommendations for improving the alignment of the PASO task with the technology needs.

1. The key points of the report relevant to architecture are:

   a. Autonomous command and control is a system-wide design attribute; it permeates all major components of the space station.

   b. Autonomous command and control are best served by a hardware architecture that is distinct from the functional architecture. Hardware architecture is characterized by a <u>centralized</u> Station Executive Controller (SEC) and a <u>distributed</u> group of subsystems control resources. Functional architecture is characterized by a <u>hierarchical</u> arrangement of the SEC and the subsystems.

   c. Self-checking, fault-tolerant computing is essential for the SEC and highly desirable for the subsystems.

   d. A low-speed, highly reliable SEC/subsystems Intercommunications Control Bus is recommended for command and control data, and a separate high-speed Data Transfer Bus is recommended for high-data-rate communications, e.g. telemetry, payload data, etc.

2. The key points relevant to autonomy technology needs are:

   a. Current technology is sufficient for implementing some degree of autonomy, but significant technology advances are needed to provide the degree of autonomy currently projected for space station.

b. The technology needs for system-wide autonomous executive control, as embodied in the proposed SEC, have not been fully addressed. Needs include:

1) The technology for providing command and control at all levels of a functional hierarchy and in all operational modes, including preflight integration and testing, in-flight validation, and normal operations.

2) A software based "operating system" is needed to provide the critical control interface between the operator (crew/ground) and the station machine. This operating system would include a Communications and Control Language for communications between the system operator (integration tester, ground controller, flight crew, and customer) and the system. A programming language, such as HAL/S or Ada, is not a Communications and Control Language. Development of the language will achieve maximum commonality as all elements of the system should share a common communications and control language. The language will serve as a unifying standard in design of the overall system control architecture and provide a common reference for all implementation contractors.

3) An autonomy test bed for validating all system-level autonomous command and control features, including communications with the system operator.

3. For the initial space station, a minimal degree of autonomy is dependent upon:

a. Fault-tolerant computing having minimal mass and power requirements and offering large memory address space.

b. High-capacity random-access memory.

c. High-capacity nonvolatile read-write memory.

d. Fault-tolerant data busses for system command and control.

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ABBREVIATIONS/ACRONYMS

ACS	Attitude Control System/Attitude Control Subsystem
ADA	DoD Standard Programming Language
AI	Artificial Intelligence
ARMMS	Autonomous Redundancy and Maintenance Management Subsystem
ASP	Autonomous Spacecraft Program
ASST	Autonomous Spacecraft Systems Technology
BIBB	Bus Interface Building Block
BITE	Built-In Test Equipment
BIU	Bus Interface Unit
C&T	Communication and Tracking
CDG	Concept Development Group
CDS	Command and Data Subsystem
DMA	Direct Memory Access
DMS	Data Management System
ECLSS	Environment Control and Life Support Subsystem
EEIS	End-to-End Information System
EPS	Electrical Power System
G&C	Guidance and Control
GEO	Geo-Synchronous Earth Orbit
GN&C	Guidance, Navigation and Control
HAL/S	Programming Language
I/O	Input/Output
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LSI	Large Scale Integration
MIBB	Memory Interface Building Block

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ABBREVIATIONS/ACRONYMS (cont)

NAV	Navigation
NVM	Non-Volatile Memory
OAST	Office of Aeronautics and Space Technology
OMV	Orbital Maneuvering Vehicle
OTV	Orbit Transfer Vehicle
PASO	Program and Specific Objectives
PROP	Propulsion
RAM	Random Access Memory
SCCM	Self-Checking Computer Module
SEC	Station Executive Controller
SS	Space Station
TBD	To Be Determined
TC	Temperature Control
TMS	Teleoperator Maneuvering System
VLSI	Very Large Scale Integration

PART 1

INTRODUCTION

1.1 OBJECTIVES

In FY`83 the ASST team analyzed space station needs for new technology in the area of autonomous systems, and evaluated the OAST program for meeting those needs. Our objectives were to:

a. Develop an understanding of the baseline space station and its needs for autonomous systems.

b. Develop a candidate functional architecture for autonomous command and control within the core space station.

c. Identify FY`84 PASO objectives/targets that are associated with the command and control architecture.

d. Identify and formulate new objectives/targets associated with the command and control architecture that are not in the FY`84 PASO.

Our accomplishment of these objectives is documented in the following two parts of this report. Part 2 describes the candidate autonomous command and control architecture. Part 3 evaluates the OAST program and makes recommendations for improving the alignment of the program with the technology needs.

1.2 METHODOLOGY

During FY`83 our activities included the following steps. These steps are listed in the logical and not necessarily chronological order.

a. Formulate a candidate autonomous command and control architecture applicable to the baseline space station.

b. Identify new requirements in the area of autonomous systems technology that are inherent in the candidate architecture.

c. Relate new-technology requirements to the OAST technology development program. Identify existing objectives/targets that support space station requirements and identify those space station requirements that are unsupported. Formulate recommendations for improving the match.

d. Document the results.

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We chose the baseline space station as documented by the Concept Development Group (CDG) of the Space Station Task Force to be the reference for development of the candidate command and control architecture. In addition to information obtained from the relevant space station documentation, members of the ASST team gained insight into the baseline space station concept through their participation with the CDG sponsored studies, the Systems and Operations Working Group, the Attitude Control and Stabilization Working Group, the JPL Space Station Information System Study, and the End-to-End Information System (EEIS) study.

The candidate architecture is focused on the core space station for the following reasons:

a. Autonomy/automation applied to the day-to-day command, control, and monitoring of the space station core provides the greatest leverage for increasing crew productivity and reducing real-time ground control requirements.

b. Basic principles derived for the space station core are applicable as well to other elements of the space station program.

c. Fundamental technologies are needed for the development of a viable space station concept. Developing more specialized technologies needed by other elements, such as the OTV and OMV, could defocus identification of the fundamental technologies.

d. The scope of effort required for a treatment of other elements is beyond currently available resources.

1.3 AUTONOMY DEFINITION AND CHARACTERISTICS

1.3.1 Definition

The following definition of autonomy describes a fundamental system-level attribute of a spacecraft system:

> "Autonomy is that attribute of a system that allows it to operate without external control and to perform its specified mission at an established performance level for a specified period of time."

There are several important points contained within this definition:

a. The "system" whose autonomy is being described must be clearly bounded to allow differentiation between the system and its external interfaces.

b. The definition implies a closed-loop control process within the bounds of the autonomous system. Human resources may be utilized in the control process if the system boundary includes a manned component. The term "machine autonomy" has been used to describe those circumstances where human resources are not normally included in the control process.

c. The "specified mission" must be defined for each individual project, program, etc. that requires autonomous operations. This mission may be the entire mission or a specific portion of the nominal mission.

d. The "established performance level" may include a specification of full nominal performance or some degraded level of performance that is adequate to satisfy mission requirements for the autonomous operation period.

e. The "specified period of time" scopes the autonomous control problem and ensures that the proposed implementation meets this requirement.

f. Autonomy implies adaptability in the closed-loop control process. This adaptability includes the ability to continue to operate at some level of performance in the presence of faults (fault tolerance, redundancy management, etc) and to maintain the specified level of system performance (calibration, health maintenance, etc). Mission-specific requirements for adaptability of the onboard control process may include the ability to select alternate control modes and sequences, to perform navigation functions, and/or to process and reduce mission data.

1.3.2 Autonomous Control Characteristics

Any implementation of autonomy is structured in the form of a three step control process. Those processes that require closed-loop control may cycle from step c. back to step a., below.

a. Sense and analyze the state of internal or external quantities.

b. Initiate a response by the system that meets an appropriate objective.

c. Act to implement the response.

An autonomous control process is implemented through control resources that utilize command and data management resources. Sensory data required by the command resource may be collected and communicated by data management resources in a manner normally used for engineering telemetry. A conventional command system may be utilized by an autonomous command resource to implement desired system- and subsystem-level state and operating mode changes. Programmable computer resources allow adaption of the direction of the control process. As system complexity increases, distribution of separate control resources to the subsystem level and below serves to reduce the pressure of multiple demands upon a central resource, reduces the interdependence of subsystems, and supports the evolvability of the system to meet new requirements.

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1.4 ACKNOWLEDGEMENTS

The work done under this RTOP in FY 1983 has been supported by a variety of JPL staff members. The team currently producing this report and performing the system level technology analysis is:

Name	Responsibilities
P. R. Turner	ASST Task Leader
C. C. Wertz	Spacecraft Systems Engineering
J. R. Matijevic	Guidance and Control/Autonomy Architecture
E. Mettler	Guidance and Control/Autonomy Architecture
W. E. Arens	Data Management, Fault-tolerant Computing
A. R. Klumpp	Navigation
K. A. Blom	Ground Systems, Mission Operations

Team activities earlier in the year involved the contributions of a number of additional subsystem specialities which were provided by:

Name	Responsibilities
R. W. Kocsis	Spacecraft Systems Engineering, ASST Team Leader
D. E. Rockey	Electric Power
R. N. Miyake	Thermal Control
J. R. High	Robotics and Teleoperation
D. D. Schmit	Propulsion
C. T. Timpe	Telecommunications
D. D. Lord	Data Management
S. Bard	Thermal Control
P. Tsou	Spacecraft Systems Engineering

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PART 2

AUTONOMOUS COMMAND AND CONTROL ARCHITECTURE

2.1 INTRODUCTION

2.1.1 Background

2.1.1.1 System/Subsystem Relationship. The term system is applied in this report to refer to the major blocks of the space station system architecture represented by the space station core, Teleoperator Maneuvering System (TMS), Orbital Transfer Vehicle (OTV), etc. The space station core is comprised of a number of functional subsystems such as the data management subsystem, power subsystem, propulsion subsystem, etc.

2.1.1.2 Autonomy. As described in paragraph 1.3.1, autonomy is an attribute of a system/subsystem that will allow it to operate within its specified performance requirements without external intervention for a specified period of time. This definition does not preclude either man or machine from the system/subsystem design. In other words, an autonomous system/subsystem may contain both men and machines. For instance, autonomy of the Space Station Core System would be achieved using both crew members and machines to provide independence from ground control.

Machine autonomy would reflect the autonomy attribute of a system/subsystem which contains no human elements within its internal boundaries. For instance, specified Space Station Core Subsystems may incorporate machine autonomy to support the overall Core System autonomy needs.

An interrelated but different attribute from that of autonomy is automation. Automation refers to the use of machines to effect control of system/subsystem processes in a predefined or modeled set of circumstances. A system/subsystem containing automation can be implemented with or without the attribute of autonomy. However, the attribute of automation can be viewed as a vital tool for implementing an autonomous system/subsystem.

2.1.1.3 Autonomous Control. A control structure logic for effecting the control processes necessary to achieve the attribute of autonomy as defined in paragraph 1.3.2 is:

a. Sense and analyze the state of an internal or external quantity.

b. Direct the initiation of a response that meets an appropriate objective.

c. Act to implement the response.

An autonomous process would use this control structure logic to assess the appropriateness of the functional operation of a system/subsystem based on internal and/or external sensory inputs and effect modifications to that operation as needed to maintain an acceptable level of performance.

2.1.1.4 Autonomous Control Resources. The control structure definition for autonomous processes implies a connection between autonomous control, data management, and command resources. For example, the sensory data needed by the control structure logic for autonomous housekeeping and maintenance functions may be collected, stored, and furnished to the autonomous control resources by the data management resources in the manner normally used for engineering telemetry. Furthermore, the normal command resources may provide the means through which autonomous control resources can implement the desired system and subsystem level state changes. A flexible/programmable autonomous control resource can be realized through use of modern computer technology. The space station requires a distribution of such computer control resources to the subsystem level and below to relieve the pressure of multiple demands upon a central resource and to reduce the interdependence of subsystems.

2.2 A CANDIDATE SPACE STATION AUTONOMOUS COMMAND AND CONTROL ARCHITECTURE

2.2.1 Architectural Tradeoffs

2.2.1.1 Overview. The early use of computer technology for spacecraft applications favored a centralized processing architecture based upon both spacecraft needs and implementation practicality. For these early applications, only a limited few spacecraft subsystems required computer support to perform their service functions. Furthermore, early spacecraft computer designs placed significant demands on spacecraft mass and power.

There is a practical limitation to how powerful one can make a single computer in terms of throughput rate. This limitation coupled with the emergence of microprocessor technology has resulted in a recent trend towards distributed processing architectures using multiple computers. An example of the use of such an architecture is found in the JPL Galileo spacecraft currently under development. The Command and Data Subsystem (CDS) functions as a central executive computer that provides high-level control via a supervisory bus to other major subsystem computers and distributed payload microprocessors. This allows the central computer to be off-loaded so that increasing demands on workload and throughput, resulting from more sophisticated spacecraft needs, can be practically accommodated. The Galileo decision to distribute some of its processing was primarily driven by the instrument computing needs of its relatively sophisticated payload.

As the complexity and sophistication of future spacecraft continue to grow, the trend should continue towards increased distribution of data handling and control functions to the subsystem level.

This will be heavily influenced by the following two factors:

a. The need for computing support to be provided for every spacecraft subsystem.

b. The availability of reliable, cost-effective, self-checking, fault-tolerant computer modules having low weight and power characteristics.

The first item should be satisfied by the future need for significant levels of autonomous operation in order to reduce the work load imposed on man. The requirement of even the most simplistic subsystem to be autonomous

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with respect to its own integrity maintenance implies the application of computer software support to adequately meet the diagnostic and recovery needs associated with fault detection and correction. The second item should be satisfied in the near future by application of state-of-the-art technology in the areas of microprocessors, memory, and LSI. In fact, JPL has breadboarded and already demonstrated a self-checking, fault-tolerant computer that uses LSI-compatible building block modules to interface with commercially available microprocessor and memory chips.

Distribution of functions to the subsystem level could theoretically be extended to the limit of being fully distributed in terms of both hardware and software. The block diagram of Figure 2-1 can be used to illustrate a fully distributed architecture assuming all subsystem-unique and subsystem interdependent functions are distributed between subsystems at the subsystem level. This implies no common executive control at the system level. Such a fully distributed approach does create certain negative attributes which may lead to the conclusion that the best architectural choice for most applications might involve a hybrid combination of decentralization and centralization of functions. A brief assessment of the major positive and negative attributes of a fully distributed architecture, when compared with highly centralized architectures, is provided in the following paragraphs. This section then concludes by identifying the advantages of a highly distributed hybrid architecture in which subsystem-unique functions are distributed but subsystem-interdependent functions are centralized at the system level under the control of a common executive level computer.

2.2.1.2 Positive Attributes of a Fully Distributed Architecture. A fully distributed architectural approach has the positive attributes described below, when compared with a highly centralized architecture.

2.2.1.2.1 High Throughput Rate and Operational Efficiency. Throughput rate and operational efficiency increases in proportion to the number of processing functions that can be performed simultaneously using parallel processors. In a highly centralized architecture, most of the processing functions required by each subsystem must be time-shared in a single common computer. This severely limits the throughput rate and operational efficiency of the system since there is a practical limit in processing capability that is feasible from a single computer based on mass and power considerations. The fully distributed architecture assumes a dedicated computing capability resident within each subsystem. Therefore, the subsystem-unique processing requirements for all subsystems may be performed simultaneously. This significantly increases the possible throughput rate and operational efficiency of the system when compared with a highly centralized architecture.

2.2.1.2.2 Low System Integration Costs. Distribution of all processing functions to the subsystem level inherently allows considerably more system independence for the test, validation, and operation of subsystems. If the integrity of the system interface requirements for a subsystem is maintained, most of its test and validation may be accomplished prior to system integration. In contrast, for highly centralized architectures, because of the subsystem dependence upon the central processor, very little subsystem test and validation can be accomplished until each subsystem is integrated into the complete system. Therefore, the normally large costs attributed to

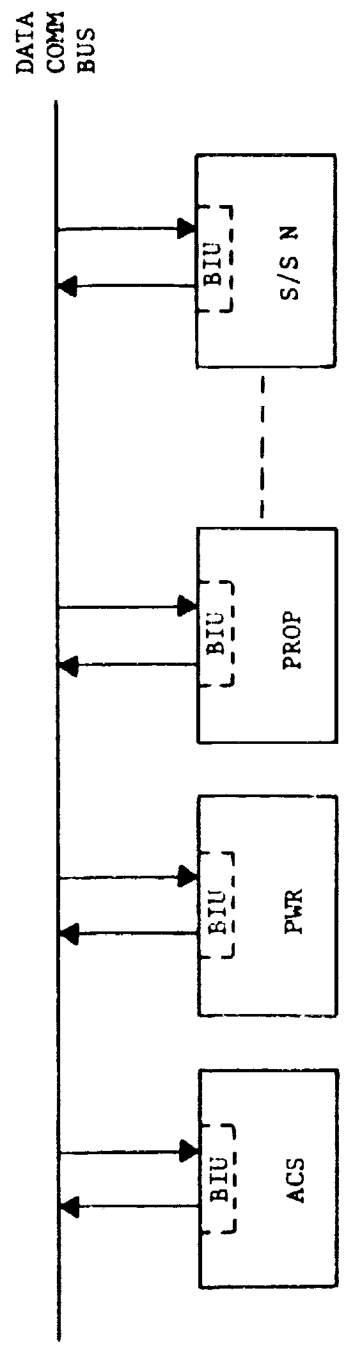

Figure 2-1. A Fully Distributed Architecture

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the spacecraft system integration, test, and operation phases for missions employing highly centralized system design architectures should be potentially reduced by the use of a fully distributed architecture.

2.2.1.2.3 Flexibility to a Wide Range of Applications. An inherent feature of a fully distributed processing architecture is flexibility for multimission applications. In contrast, a highly centralized system design architecture tends to be mission-dependent since the performance capability of the central computer has profound effects on the operating limitations of all subsystems. Fully distributed processing, in general, allows considerable system independence for the internal design and operation of subsystems assuming the integrity of subsystem external interface requirements is maintained.

2.2.1.2.4 High Level of Evolvability. A fully distributed system design architecture inherently provides a high level of evolvability or growth potential. The internal processing capability of individual subsystems can be significantly increased with little effect on the system design architecture. This is primarily due to the fact that each subsystem can simultaneously perform its processing functions in parallel with other subsystems. Furthermore, more subsystems can be added to a common intercommunications bus limited only by bus traffic capability. In contrast, the growth potential is considerably more limited for a highly centralized architecture since the processing and control requirements for all spacecraft subsystems must be accomplished by a single computer on a time-shared basis placing practical limitations on achievable throughput rates and operational efficiencies.

2.2.1.3 Negative Attributes of a Fully Distributed Architecture. A fully distributed architecture also has some potentially serious negative attributes. The two most significant with respect to technology readiness and cost are described below:

2.2.1.3.1 Numerous High-Performance Fault-Tolerant Computers. The very nature of a fully distributed architecture increases the number of spacecraft computers when compared with highly centralized implementations. Furthermore, since they have no central executive to monitor their health, each subsystem must provide a self-checking fault-tolerant computing capability for autonomous operation. Assuming the architecture requires all system-level intercommunications between subsystems to be accomplished through a common high-speed bus network, high-performance fault-tolerant computing will be required for subsystem intercommunications. This reflects into a potentially very complex bus interface unit (BIU) hardware/software design.

2.2.1.3.2 High-Complexity System-Level Software. Although there are many subsystem-unique processing functions that can be distributed to their respective subsystems, there still remain numerous service and autonomy-related functions that are subsystem-interactive. These interactive functions involve the need for executive system-level prioritization, arbitration, and decision making. In this case, distribution of such functions becomes a handicap when compared with a centralized approach. For a fully distributed system design architecture, the system-level executive software responsibilities must be distributed between multiple subsystem computers. This requires an early top-down system design effort in which the subsystem responsibilities for meeting the system-level needs are properly allocated and

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well defined. If this is not adequately done, it could potentially impact multiple subsystem software designs later in the program as opposed to one software design if the executive control for subsystem interdependent functions were centralized.

2.2.1.4 Advantages of a Hybrid Architecture. A candidate hybrid architecture employing distribution of the subsystem-unique data handling and control functions, but centralization of the system-level executive control function, could significantly reduce the negative attributes of a fully distributed system. For instance, only one fully self-checking fault-tolerant computing capability is required in the entire space station and this can have relatively low throughput characteristics. Furthermore, the BIU function for the potentially high-speed data bus can be relatively simple since it only has to execute direct memory access (DMA) read/write functions with a single memory interface. And, finally the system-level software implementation task can be significantly reduced in magnitude.

2.2.2 Conceptual System-Level Architecture Description

A candidate system-level autonomous command and control architecture for the space station in which the subsystem-unique processing functions are distributed to their respective subsystems while the subsystem interdependent functions are centralized at the system level is conceptually illustrated in Figure 2-2. The most significant feature of this architecture is that it retains all of the positive attributes of a fully distributed architecture while effectively removing the negative attributes of that architecture.

The architecture of Figure 2-2 includes a Station Executive Controller (SEC) plus TBD number of subsystems interconnected by two separate bus networks. The SEC and each subsystem is a bounded set of hardware and software elements, as required to perform its functions. Each is computerized, relatively independent of the others, and fault-tolerant.

2.2.2.1 Station Executive Controller. The SEC performs the system-level executive control functions required for mission operations, interactions between subsystems, and subsystem fault tolerance. The SEC contains a central memory bank for storing updated space station information to be accessed by subsystems, the crew, and ground operations as required. SEC computing facilities are self-checking and highly fault-tolerant. Although not shown in Figure 2-2, the SEC can be redundant and may be implemented within several space station modules including the safe haven.

2.2.2.2 Low Bandwidth Intercommunications Control Bus. A key concept for the architecture of Figure 2-2 is a separate intercommunications bus for the relatively low bandwidth system-level control and autonomy-related functions. By using a separate bus for the higher-bandwidth continuous-demand functions such as telemetry data transfer, the intercommunications control bus traffic needs will be significantly less demanding allowing the transfer efficiency of control and autonomy-related information to be maximized. Furthermore, this allows the SEC to accomplish the system-level autonomy functions with a dedicated self-checking fault-tolerant computing capability having relatively low-throughput requirements. The enabling technology has already been

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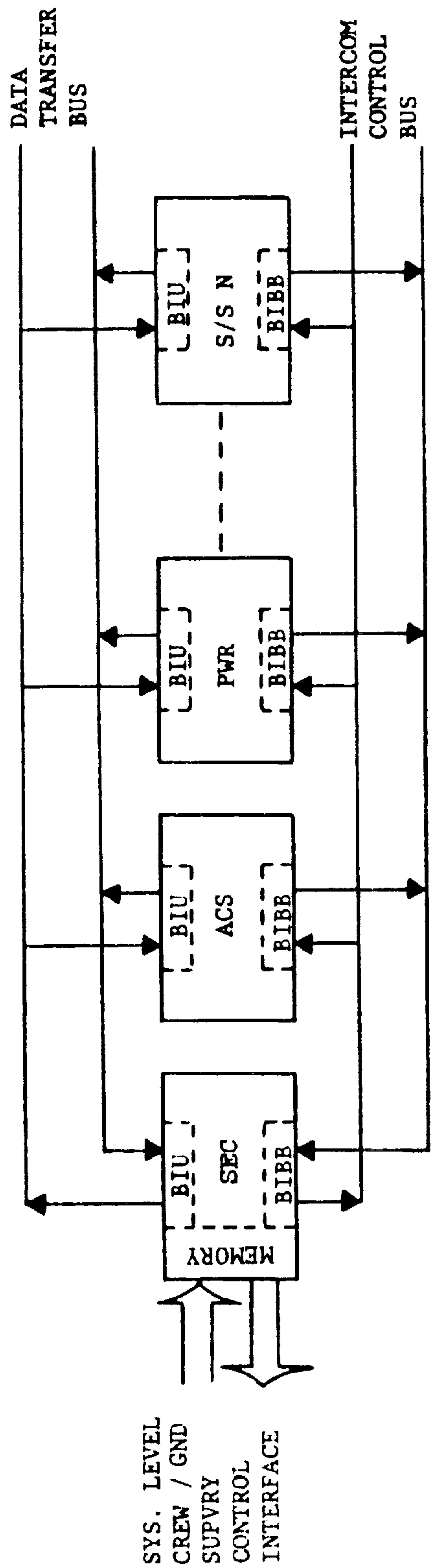

Figure 2-2. A Space Station Hybrid Architecture

demonstrated for such a low-bandwidth capability in the form of the Self-Checking Computer Module (SCCM) breadboard developed by JPL under the joint sponsorship of the U.S. Navy and NASA OAST during the past 5 years. Currently the fault-tolerant intercommunications control bus with SCCMs interfacing through fault-tolerant Bus Interface Building Blocks (BIBBs) is being developed in a testbed at JPL as part of the Autonomous Redundancy and Maintenance Management Subsystem (ARMMS) Demonstration Project under USAF sponsorship. It will be used as part of a communications satellite autonomy demonstration in FY'86 to show proof-of-concept for flight applications. NASA is currently supporting this effort in the area of the BIBB design as part of the Joint Air Force/NASA Interdependency Program. In addition, one of the SCCM building blocks, the Memory Interface Building Block (MIBB), is being implemented using flight qualifiable gate array technology to demonstrate applicability of that technology in achieving low chip counts and power characteristics. This gate array implementation of the MIBB will also be part of the initial FY'86 ARMMS demonstration. By taking advantage of the technology being developed in the ARMMS testbed (the self-checking fault-tolerant computer capability, the fault-tolerant bus, and the fault-tolerant BIBBs as depicted in Figure 2), the development of the space station executive control capability should be achievable at a relatively low risk and cost.

2.2.2.3 Data Transfer Bus. With the executive control effected by the SEC through the low-bandwidth fault-tolerant intercommunications control bus, the role of the comparatively higher-bandwidth data transfer bus can be relatively simple. For example, this bus could represent a DMA interface for each subsystem user to the central memory bank in the SEC. As such, each subsystem, when provided access to the data transfer bus by the SEC, would simply write updated information into predefined addresses of protected SEC memory (for access by other subsystems, the on-board crew, or ground operations) and read out appropriate data that was sent to it from other subsystems, the on-board crew, or ground operations. This relatively simple data transfer function would represent a single digital interface (SEC memory) for each subsystem user of the bus.

2.2.2.4 Major Attributes. The hybrid autonomous control architecture of Figure 2-2 possesses all of the same positive attributes previously identified for a fully distributed architecture. These are as follows:

a. High throughput rate and operational efficiency.

b. Low system integration costs.

c. Flexibility to a wide range of applications.

d. High level of evolvability.

Using the SEC and a dual bus system to perform executive-level control functions, involving subsystem interdependency, separate from higher-speed data transfer functions enables the negative attributes defined for a fully distributed architecture to be either resolved or significantly reduced in magnitude. The resulting additional positive attributes are listed in the following subparagraphs.

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2.2.2.4.1 Simplicity of Subsystem Interfaces. All subsystem interfaces are fully digital. Furthermore, each subsystem has a signal interface at the system level with only the SEC. The control interface is via a low bandwidth bus and provides both man and machine supervisory control in a manner which is transparent to the subject subsystems. The data transfer interface for each subsystem is a single DMA interface through a comparatively high-speed data transfer bus with the SEC memory. Since memory access will be prioritized and controlled by the SEC, use of the bus by a subsystem for writing into and reading from memory will be accomplished on a noninterference basis.

2.2.2.4.2 Efficient Interactive Information Transfer Between Subsystems. Use of the SEC to provide centralized executive control of subsystem intercommunications and system-level decisions on a separate bus from that used for higher-speed continuous-demand data transfer functions should significantly increase operational efficiency. For instance, the SEC could readily reassign priorities to provide adaptive time slot allocations between subsystems as a function of mission need.

2.2.2.4.3 Minimal Self-Checking Fault-Tolerant Computing Demands. A dedicated self-checking fault-tolerant computer processing capability is required by the SEC since there is no external means of providing SEC computer fault management during fully autonomous operation. However, using this capability, the SEC can provide health monitoring and fault management services to subsystem computers as required. Although each subsystem will use its own dedicated computers to autonomously perform its own designated service functions and maintain its own health and welfare, subsystem computer fault management support from the SEC removes the need that these subsystem computers be fully self-checking and fault-tolerant. Nevertheless, it will probably be desirable to also use self-checking fault-tolerant computers in major subsystems where appropriate. For instance, a fully fault-tolerant capability using the aforementioned SCCM technology would be entirely feasible for a subsystem executive-level computer having a dedicated low-bandwidth interface with the intercommunications control bus.

2.2.2.4.4 Minimal System-Level Software Complexity. For a fully distributed system design architecture, the system-level control and autonomy-related functions, where more than one subsystem is involved, must be performed by a set of software fault routines which are distributed among memories of the various subsystems (probably in fault-tolerant highly complex subsystem-dedicated BIUs). The subsystem software routine complexities can be significantly reduced by allocating system-level executive responsibility to the centralized SEC of Figure 2-2 for such subsystem interdependent conditions. The increase in software complexity imposed upon the SEC should be small compared with the total software complexity reduction realized by the subsystems when taken as a whole. This is attributed to the greater efficiency that can be realized by using the SEC for executive control of subsystem interdependent functions.

2.2.2.4.5 Simple User-Transparent Man/Machine Supervisory Interface. In contrast to a fully distributed architecture, the SEC of Figure 2-2 provides a centralized single-point of supervisory control at the system level for all subsystems. It also, via the data transfer bus, retains all pertinent updated space station system-level data in its memory bank. This is readily

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accessible by the SEC for effecting autonomous operations and control. It also allows man to extract information in a manner that is transparent to the space station subsystems. Man (crew or ground-based) can also effect supervisory control through the SEC in non-autonomous or supervisory modes of operation. Again, at the subsystem level such control can be virtually transparent and nonconflicting.

2.3 A CANDIDATE STATION EXECUTIVE CONTROLLER (SEC) ARCHITECTURE

The SEC of Figure 2-2 provides a central system-level computing capability that services space station subsystems. Although not shown in Figure 2-2, it is assumed that the SEC will be redundant and that this redundancy will be implemented at several different physical locations to increase the overall system-wide reliability. Furthermore, it is assumed that the SEC will be readily accessible by crew members at work station terminals in all of the manned space station modules. The following subsections a) define some preliminary SEC functional and interface requirements and b) describe a candidate SEC design approach for illustrative purposes.

2.3.1 Functional Requirements

The major functional requirements imposed upon the SEC by the hybrid system design architecture of Figure 2-2 are defined as follows:

a. Decode, validate and distribute plain-text commands received from on-board crew members and the ground.

b. Monitor the status of all space station subsystems and provide executive-level control of all functions involving interactions/interdependency between subsystems.

c. Receive and file updated engineering data when provided by space station subsystems or the ground.

d. Generate and store system-level space station audit trail data records.

e. Store critical space station software and data in protected nonvolatile memory (NVM).

f. Provide specific stored data to space station subsystems, on-board crew members, or the ground when requested and/or required.

g. Provide executive-level health monitoring and redundancy management of space station subsystem computers as required.

h. Provide self-maintained fault tolerance to all internal single-point failures.

i. Distribute a common timing signal to all space station subsystems.

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2.3.2 Interface Requirements

The signal interface requirements imposed upon the SEC by the hybrid system design architecture of Figure 2-2 are defined as follows:

a. Provide a digital data transfer bus interface with each space station subsystem for the purpose of acquiring and disseminating engineering and audit trail data.

b. Provide a digital intercommunications control bus interface with each space station subsystem for the purpose of effecting autonomy-related fault management and routine maintenance functions.

c. Provide an external digital interface with SEC memory for the purpose of a) providing engineering and audit trail data to on-board crew members upon request and b) receiving commands from on-board crew members.

2.3.3 Hardware Functional Description

A functional block diagram for a candidate SEC design architecture is given in Figure 2-3. A brief description of each of the hardware functional elements of the SEC is given in the following subparagraphs.

2.3.3.1 Input/Output (I/O) Unit. The I/O unit receives and buffers all data transferred in and out of the SEC. This includes: a) DMA for engineering and audit trail data transfer to and commands from on-board crew members; b) data transfer bus traffic for engineering/audit trail data transfer between space station subsystems and to the ground; c) data transfer bus traffic for ground commands from the space station subsystem receiving the uplink commands; and d) intercommunications control bus traffic for the transfer of interactive information between and executive-level commands plus timing to the space station subsystems. It also decodes the plain-text commands received from on-board crew members and the ground. As noted from Figure 2-3, the I/O unit interfaces directly with the self-checking fault tolerant computer and the nonvolatile mass memory within the SEC. The SEC bus interface circuits (BIBB and BIU) as noted in Figure 2-2 would be included as part of the I/O unit.

2.3.3.2 Self-Checking Fault Tolerant Computer. The self-checking fault-tolerant computer block of Figure 2-3 interfaces directly with the I/O unit and the nonvolatile buffer memory. It performs the data processing functions required to effect the system-level executive control needed for space station autonomy. All space station system-level data and command transfer, with the exception of audit trail readout to on-board crew members and the ground, is accomplished through a volatile random-access memory (RAM) in the self-checking fault-tolerant computer block. The necessary software routines associated with immediate and near-term SEC use are also stored in this memory. The self-checking fault-tolerant computer block uses the information and software routines stored in RAM to format the real-time output telemetry data stream which it provides to the I/O unit. It also provides non-real-time telemetry, audit trail data, and ground updated software routines to the nonvolatile buffer memory for storage.

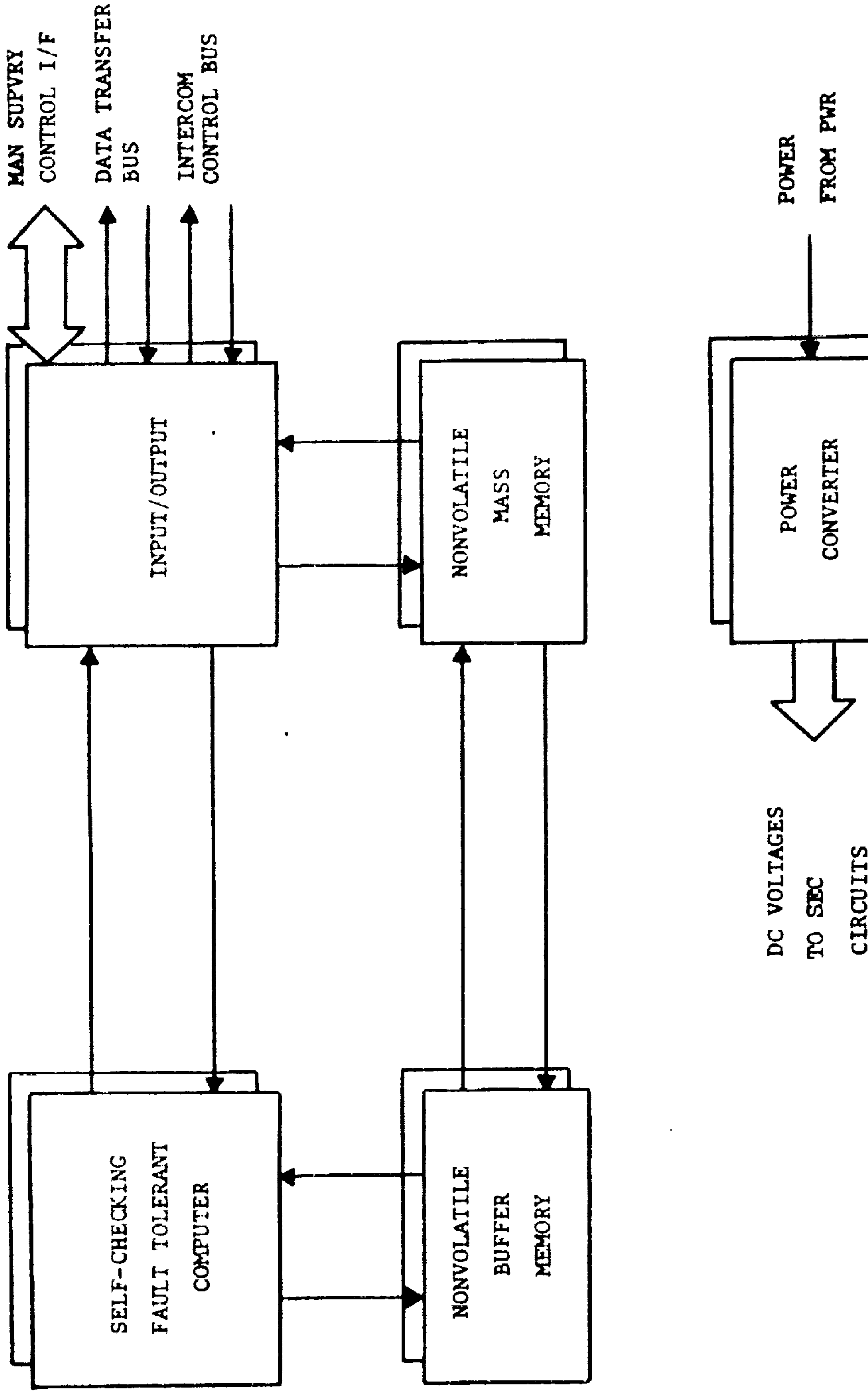

Figure 2-3. Station Executive Controller

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Referring to Figure 2-3, the self-checking fault-tolerant computer block provides the fault detection, fault isolation, and correction command issuance for not only itself but all remaining functional elements directly associated with the SEC. This includes the nonvolatile buffer memory, the nonvolatile mass memory, the I/O unit, the power converter unit, the data transfer bus, and the intercommunications control bus all of which are redundant.

A simplified block diagram of a candidate self-checking fault tolerant computer block is provided in Figure 2-4. Referring to Figure 2-4, two standardized building block modules are used to effect the self-checking and repair functions associated with the microprocessor and memory. The Core building block and the Memory Interface Building Block (MIBB) can be interfaced with virtually any commercially available 16-bit microprocessor and memory chips to provide a fault-tolerant self-checking computer module (SCCM). Single error detection and correction are provided for memory transient faults by adding 6 bits of Hamming code to each 16-bit word. Since memory transient faults in the form of bit flips are the most prevalent source of faults, this significantly improves the reliability of the computer. The next most prevalent source of faults occurs due to internal bit flips in the registers and state flip flops of the microprocessor. Fault detection is provided by adding a second microprocessor to provide a comparison with the first. When transient errors occur, a disagreement between computer outputs occurs whereupon a software rollback function can be performed to provide recovery. Permanent faults in memory can be tolerated by providing two spare bit planes. A permanent hardware fault in a given memory bit location can be corrected by switching in one of the spare bit planes. Finally, recovery from a permanent fault in a given microprocessor can be accomplished by adding a third microprocessor. When a permanent fault occurs, where recovery cannot be effected, the SCCM affected will notify a "hot" spare backup and will disable itself. The spare SCCM will then take over for the failed unit.

2.3.3.3 <u>Nonvolatile Buffer Memory</u>. The nonvolatile buffer memory interfaces directly with the self-checking fault tolerant computer RAM and the nonvolatile mass memory. It stores critical space station software routines for access by the self-checking fault tolerant computer RAM when required. Audit trail data and ground-updated software routines are received from the self-checking fault tolerant computer RAM and buffered to the nonvolatile mass memory. The nonvolatile buffer memory also buffers selected audit trail data and software routines from the self-checking fault-tolerant computer when requested by the computer.

2.3.3.4 <u>Nonvolatile Mass Memory</u>. The nonvolatile mass memory interfaces directly with the nonvolatile buffer memory and the I/O unit. It stores all pertinent space station system and subsystem software routines for access by the self-checking fault-tolerant computer RAM through the nonvolatile buffer memory. Blocks of audit trail data are received from the nonvolatile buffer memory and stored for extended periods of autonomous operation. The audit trail data is then read out to on-board crew members or the ground through the I/O unit upon request. The nonvolatile mass memory also provides selected audit trail data to the self-checking fault tolerant computer via the nonvolatile buffer memory when requested by the computer.

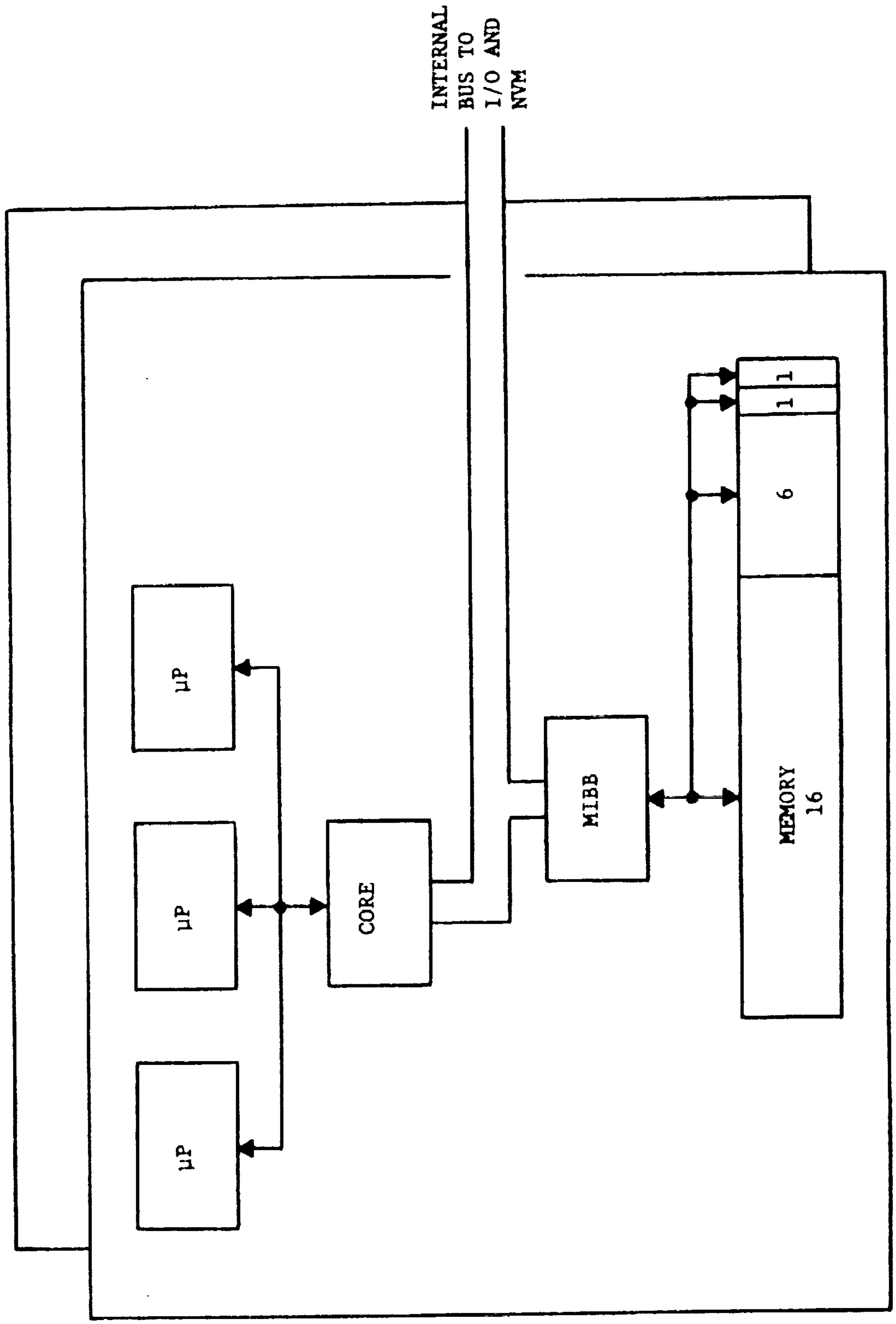

Figure 2-4. Self-Checking Fault Tolerant Computer

2.3.3.5 Power Converter. The power converter in Figure 2-3 interfaces with all other elements of the SEC for power distribution purposes. It receives raw power from the appropriate space station Power Subsystem (PWR) and generates the required voltages for autonomous SEC operation. It then distributes these generated voltages to the appropriate SEC circuits.

2.3.3.6 Intercommunications Control Bus. The intercommunications control bus identified in Figure 2-2 provides communications between all spacecraft subsystems via the SEC memory bank. It is implemented with appropriate protocols so that all data transfer is under SEC self-checking fault tolerant computer control.

2.3.3.7 Data Transfer Bus. The data transfer bus identified in Figure 2-2 provides direct memory access (DMA) to the SEC self-checking fault-tolerant computer RAM. It effectively off loads the engineering telemetry function from the intercommunications control bus. This provides access by space station subsystems to designated SEC memory bank locations for the transfer of data.

2.3.4 Executive Software Functions. The SEC executive software functions can be separated into three areas--control, support, and health. Control functions provide scheduling and sequencing of SEC operations such as input data gathering, output data transmission, subsystem health and maintenance algorithms, and internal SEC configuration changes. Support functions provide data handling facilities for use by control and health algorithms. These facilities include formatting, arithmetic processing, memory readout, and audit trail record/readout. Health functions provide internal SEC fault tolerance. These functions include computer-unique operations such as internal error reset and entry, memory bit error detection and correction, and memory analysis and bit-plane replacement. Other non-computer-unique health functions include power off/on and program error recovery. A few representative functions from each of the foregoing areas are briefly described for illustrative purposes as follows:

a. Control Functions

1) Scheduling is by real-time synchronous control. The real-time interval is assumed to be a telemetry main frame period. The assumed real-time interval is divided into variable length foreground and background processing periods. The foreground period is used to execute space station control and support functions. The background period is used to execute SEC internal self-test health functions.

2) Clock Handling is a simple synchronous counting function which is driven by the real-time interval used for scheduling. A time format is assumed based on telemetry master and main frame counts. For navigation purposes, a constant relationship between SEC executive time and navigation ephemeris time would be maintained. SEC clock timing would be synchronized to a TBD space station frequency source.

3) Crosscheck/Switchover is a function which is used to check the operation of the primary self-checking computer module (SCCM) in the SEC self-checking fault tolerant computer of Figure 2-3 and switch to a spare SCCM if the primary SCCM fails. For a configuration which consists of a primary and standby hot-spare SCCM, an inter-SCCM time synchronization and communications function will be required to periodically update the standby hot-spare SCCM memory with key parameters.

b. Support Functions

1) Telemetry Formatting of both input and output telemetry data is the function which is required to properly manipulate telemetry into a form for (a) internal SEC algorithm use and (b) for telemetry outputting.

2) Time Formatting/Manipulation functions are processes to convert between time bases e.g., SEC executive and navigation ephemeris time, add and subtract times, and time field compression and expansion.

3) Audit Trail Handling is the function which responds to requests to store data in Nonvolatile Memory (NVM) and to read out parts of, or the entire NVM. Audit trail store requests will be time-tagged at the time of the request and stored directly in NVM if audit trail readout is not in progress. Otherwise, requests will be buffered and then recorded at the normal completion of audit trail readout. Data stored in NVM will be uncoded variable length records containing first the requester identifier and SEC executive time, and then the variable length data followed by an end-of-file marker.

c. Health Functions

1) Reset is the function which responds to both power-up conditions and internal SEC computer errors. Power-up processing includes initialization of the SEC from NVM. SEC error processing includes recording and reset of the error condition and initiation of memory analysis and/or rollback/restart.

2) Self Test is a background function which is activated to perform both hardware and software SEC functional tests. Error detection results in Reset. Multiple errors result in Crosscheck/Switchover.

3) Program Error Handling is a function which is activated to respond to software generated error conditions such as arithmetic overflow, divide by zero, illegal instructions, and buffer overflow. The error response varies with severity of the condition from simple recording of the event to entry to Reset or Crosscheck/Switchover.

2.4 DETAILED DESCRIPTION OF THE CANDIDATE ARCHITECTURE

2.4.1 Partitioning of Functions.

2.4.1.1 Throughput. The allocation of control and processing resources in an autonomous subsystem is in part determined by the complexity of the functions of that subsystem and in part a function of the need to interface at the system level in the accomplishment of mission objectives. A partitioning of a system into subsystems, which provide relatively independent performance of specific functions, aids in achieving the throughput and processing required in a complex system. Once so partitioned these subsystems execute functions in parallel. However, integrated systems require periodic coordination of subsystems and functions, particularly in autonomous operations associated with fault protection or performance evaluation. Information from the subsystems must be transmitted to a higher level controlling resource where analysis takes place and commands are generated to initiate recovery or new modes of operation. This controlling resource may be entirely at the system level (SEC) if the subsystem is suitably simplified in design. However, in complex systems this resource must be shared between the system level and suitable `system` control resources in the subsystems. Such further partitioning reduces computational and interaction bottlenecks inherent in a single resource design.

2.4.1.2 Data Transmission Reliability. An additional factor in the partitioning of the control resources in a highly complex system can be the amount of information needed in the analysis of the state of the system. If this information, characterized by quality and rate of data, exceeds the bandwidth of reliable transmission, a data pre-processing function must be performed which compresses the data and transmits the result to control resources. Such partitioning implies a hierarchy of control and data processing functions which can be as extensive as system throughput constraints dictate. For example, high data rates associated with the output of optical or inertial sensors will require further compression and formatting consistent with at least the dual use of these devices in fault identification and routine control functions. Unless a scheme is implemented in the subsystem architecture which relieves the burden on interface communications, the bit error rate associated with high rates of data can critically impact the degree and cost of the hardware and software fault tolerance needed for reliable communications.

2.4.1.3 Hierarchical Partitioning by Bandwidth of Transmission. A hierarchical partitioning by bandwidth of transmission is a scheme which aids in achieving data transmission reliability. The most data-communication-intensive functions are localized to the lowest possible `level` in the hierarchy. At each succeeding level the data is transmitted at a lower rate. Signal conditioning, such as bit error correction, adds input reliability up through the hierarchy to those control processes which must draw conclusions about the state of a collection of given system processes. Control processes generate and issue commands which affect the state of those functions and devices at lower levels in the hierarchy. These commands may be in the form of objectives for system or subsystem action at the highest point of initiation. However, distribution through successive layers in the hierarchy of these commands results in interpretation of the objectives and decoding of commands into bilevel switching of subsystem elements.

2.4.1.4 Support for Crew Interaction. A hierarchy of control and data processing serves the needs of crew-interactive systems. Data compressed and processed through the hierarchy of subsystems reaches the crew in a formatted form suitable for human interpretation. Any human response to the state of the system can be structured through acceptable command states, devised perhaps through natural language interactions with the machine interface. The resultant commands then become high-level objectives interpreted by the system and executed through the appropriate levels of the heirarchy. The crew can then be 'system managers' whose system control responsibility is limited to supervisory control of a highly automated spacecraft. However, the unique contribution of man in a space system environment will result in other forms of interaction. Periodic payload operations and changeouts of equipment, which are conceived to be a part of the crew functions in a space station, will require more direct control interfaces to be supported by autonomy in the engineering subsystems. Any manner of direct crew control implementation will require input validation to avoid interference with system functions outside of the specialized crew interaction. By treating the crew input as subsystem input with the potential for error, a hierarchical system can fulfill the necessary system requirements of fault trapping and fail-operational design.

2.4.2 Autonomous Command and Control Architecture: Guidance, Navigation and Control (GN&C) Example.

2.4.2.1 Introduction. To illustrate these aforementioned principles of partitioning of functions the following example architecture using the subsystems of attitude control, precision pointing control, navigation and manipulator control in a space station environment is presented (see Figure 2-5). In this architecture the functions of the subsystems are partitioned into levels reflecting considerations of control and data transmission bandwidth. At the highest level (Level 0) this architecture applies the hybrid architectural concept described above (see paragraph 2.2). The SEC communicates with the four subsystems through executive subsystems designed in part to support the command and data handling required at the station command and control level (see Figure 2-6). Low bandwidth data transmission in support of control functions is a characteristic of this level of the architecture. As discussed below, such transmission rates are consistent with the fault tolerance required for reliable, autonomous operations of the station system. At succeeding levels of the architecture, higher bandwidth data rates required for real-time control can be provided through computing and transmission networks more tightly coupled than the hybrid computing architecture at the station command and control level. The following paragraphs detail constraints and implementation options for the functions in this example system.

2.4.2.2 Local Devices (Level 4).

2.4.2.2.1 'Smart Devices'. At the lowest level of the architecture (Level 4) reside 'smart' devices. These devices consist of actuators and sensors, integrated with microprocessors, which decode digital data commands and which encode analog outputs. Depending on the device, the digital output data, processed by these devices, can be tailored into a variety of outputs for specific use at the next higher level of control. For example, time sequences of encoded star position data may be processed into two axes of rate and

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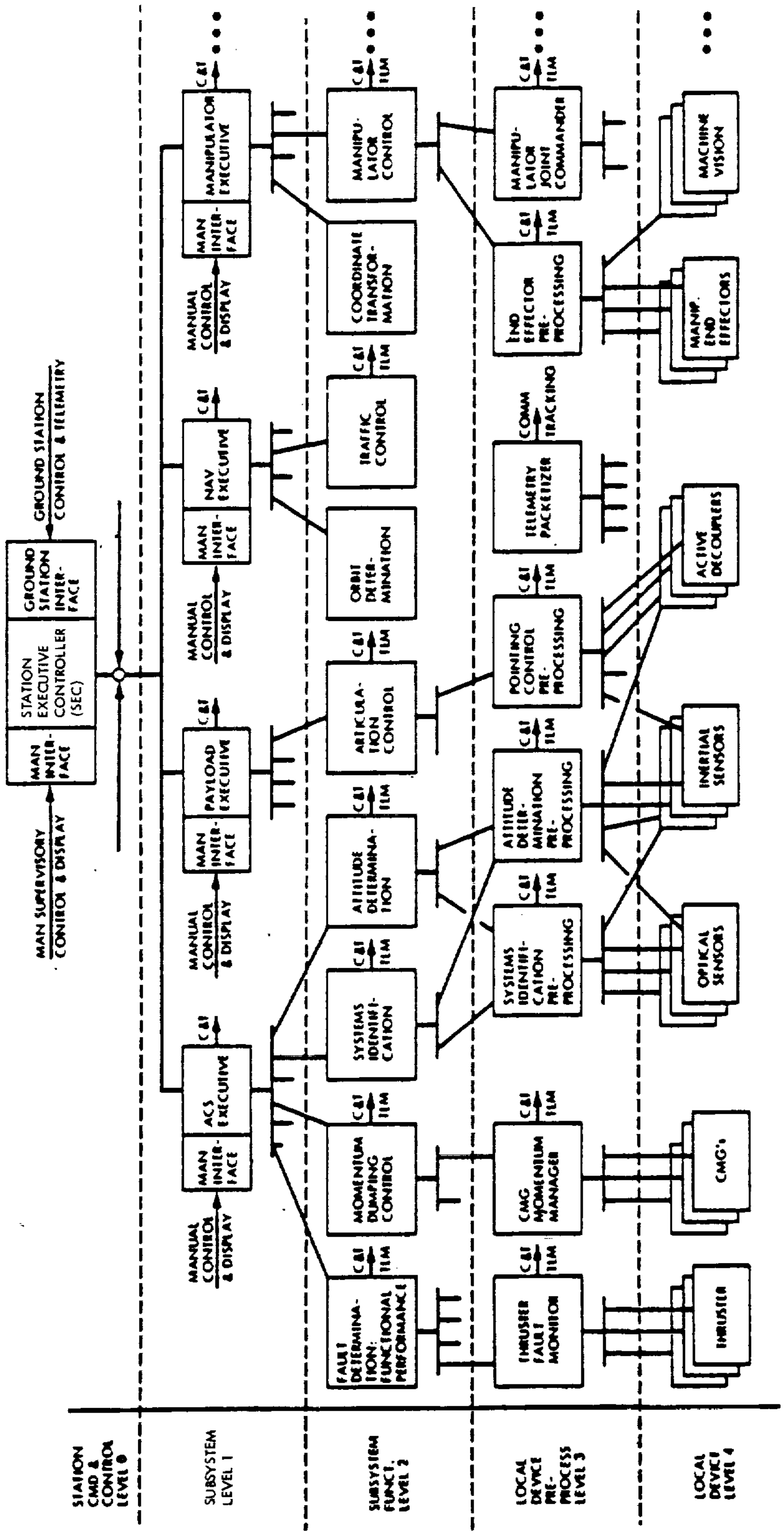

Figure 2-5. Autonomous Command and Control Architecture

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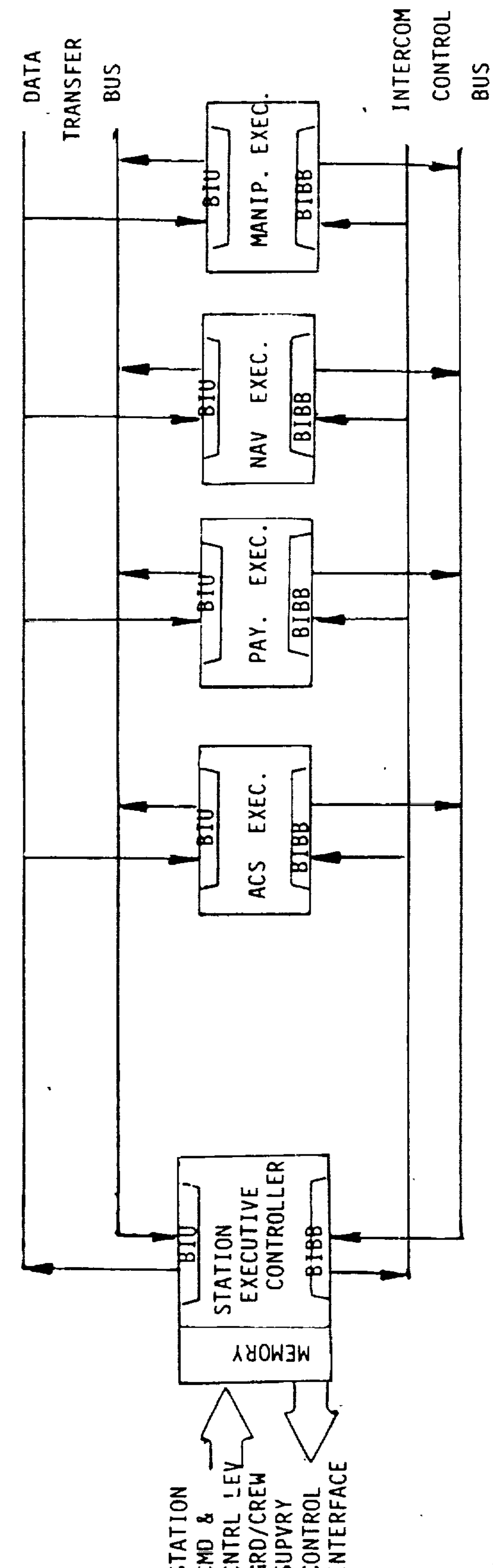

Figure 2-6. Station Command and Control

position input for a station attitude control law. Alternately, an average of the position values can be input directly into a process which derives data types for subsequent input into an orbit determination computation. More extensive processing may be necessary at this level if, for example, an optical sensor outputs images at a video rate which must undergo Fourier transformation before the resultant frequency spectrum is input to a systems identification algorithm. This sensor can be mounted at the end of a manipulator and may also be used as part of an automated monitoring task of space station structural dynamics. Thus the output would require a different type of processing, consistent with a potential tracking and feature extraction functions. Commands input into these devices can be in the form of data decoded by the integrated electronics into calibration parameters or a configuration of redundancy.

2.4.2.2.2 Device Fault Tolerance. Depending on device complexity, a degree of fault tolerant control can be introduced at this level of the architecture. If the device is internally redundant, simple comparison tests or voting of redundant output can be used to identify faults. However, verification of faults or fault isolation and recovery will usually require the participation of functions at higher levels in the architecture. As an example, consider a package of three, dual-gimballed, rate integrating gyros used as a source of spacecraft inertial reference. If properly aligned with the axes of control, only two gyros are required to sense 3-axis position, with redundancy on one axis. In any inertial hold mode of control, a simple comparison of the output of the two gyros on the redundant axis can provide a means of determining the presence of a fault. However, since such a comparison test cannot yield unambiguous results, comparison with a functionally redundant sensor, for example a star tracker, may be required to correctly isolate a failed gyro in the package. This comparison test for fault isolation would be awkward to perform at the device level since the correct determination of attitude is involved in such a test. In a complex system, attitude determination results from an analysis of a variety of sensing sources, and hence is naturally performed at a higher level in the architecture. At such a level then the comparison of functionally redundant sensors can conveniently be made. Further, sensor fault recovery can be initiated at this higher level where transitory anomalies in attitude during the recovery can be avoided perhaps through the temporary use of functional redundancy or attitude disturbance estimation. Proper device fault isolation and recovery imply a hierarchical partitioning by complexity of fault analysis and responsibility for integrating recovery with the parallel execution of real-time control functions. The extent of such partitioning is a key technique in the design of a hierarchical control architecture. By introducing fault trapping at the device level, the subsystem effects of a fault can be considered and dealt with at the next and succeeding levels in the architecture.

2.4.2.2.3 Safety. One further function performed by smart devices at this level of the architecture is the localization of hardware safety. Short-to-ground failures in electronics in the devices or in the interfaces to the next higher level result in the loss of only one device. A cascading, catastrophic failure throughout the subsystem is thus prevented. In addition, as part of the recovery process designed into the subsystem at each level of the architecture, serious failure will result in at worst a graceful degradation

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in performance of the subsystem as a whole. Functionally redundant devices can be brought into play in the subsystem while unaffected parts continue to function. This strategy in design satisfies the needs for safety in a man-rated system and is another feature of this hierarchy.

2.4.2.3 Subsystem Local Device Pre-processing (Level 3). To satisfy the need for additional data processing of input signals and output commands, dedicated subfunctions can be implemented which connect a set of smart devices at the preprocessing level (Level 3) in the subsystem hierarchy. Such subfunctions, for example, accept the conditioned signals from several sensing devices and develop from these inputs an attitude error vector. Alternatively, other subfunctions may collect sensor data from several sources and edit such inputs for use in an orbit determination process. Also, as an intermediate level in the architecture, these subfunctions perform input and output validation and interpretaton consistent with the hierarchical approach to fault protection beginning at the local device level. Lastly, selected sensor and actuator engineering data can be prepared at this level of the architecture for transmission to the communications and tracking subsystem on the space station. As a result, data generated by the devices at the lowest level can be collected and perhaps further processed or packetized depending on the choice made by the ground crew for the output of this data. Interference with other subsystem functions making use of the data from these devices is then avoided.

2.4.2.4 Subsystem Functions (Level 2). Data prepared at the local device preprocessing level of the architecture is transmitted to the next higher level (Level 2), where subsystem functions are performed. At this level complex computations associated with subsystem specific tasks such as attitude determination, orbit determination and payload pointing control can be easily performed given that the burden of input processing and output command generation has been done at the lower levels of the architecture. Consequently, the computational throughput requirements of the functions at Level 2 can be met by machines tailored for specific processing tasks. For example, a 32-bit microprocessor may be chosen to implement the precision processing needed for a trajectory prediction function. This microprocessor need not also have the capability of accepting high-rate sensor data used in the computation. The required input for the trajectory prediction has been preprocessed by separate microprocessors, designed to accept the sensor data, and this input has been transmitted at a lower rate for the trajectory computations. This illustrates one more benefit of the hierarchical subsystem architecture: the capability for the use of specialized hardware is designed into the system. As a result, new technology in (for example) microprocessor design can be introduced at a specific level of the subsystem, perhaps slaved to an existing subfunction processor as an initial implementation. The design can be tested at this level in an operational environment and eventually replace a processor at this level, transparent to the functional performance of the system.

2.4.2.5 Subsystem Executives (Level 1). At the next level (Level 1) of the architecture, subsystem functions are controlled by local executives for each of the represented station subsystems: attitude control, precision pointing control, navigation and manipulator control. An executive here utilizes the results of several subsystem functions performed at the lower levels of the

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architecture. These results can be checked for reasonableness by the executive before further action is taken. The executive can then issue high level commands to subsystem level functions initiating major control activites. Specific station system-level functions can also be performed at this level. For example, an attitude control executive can change space station attitude, prior to terminal rendezvous and docking with the Shuttle. A navigation executive can order a correction in orbit inclination. A payload pointing executive can slew a telescope to perform an observation ordered by a mission specialist or ground-based scientist. A manipulator executive can respond to a crew command to move a manipulator arm to engage a piece of equipment outside of a pressurized station module. These types of global system functions can be directed either through an autonomous SEC or by the flight crew using appropriate analog devices (joysticks, etc.) and displays. At this level of the architecture the manned and autonomously controlled actions `look` alike, in that the subsystem executives form a structured interface for the initiation of subsystem functions. As such, in keeping with the degree of impact, both the crew inputs and autonomously directed control actions will require reasonableness validation performed by subsystem executives. A part of this validation in the case of crew inputs can be achieved through the design of the input devices. Appropriate warnings, which become part of the displays, are issued by the subsystem executives in the presence of unacceptable or improper crew directed actions.

2.4.2.6 Station Command and Control (Level 0). Further protection and validation of activities at this level of the architecture is achieved through the supervisory executive control of the SEC. This executive control resides at the highest level (Level 0) of the example architecture where the communication takes place between this executive and the station subsystems. Those actions by the subsystems with station-wide impact receive high level `go/no go` sanctions from this executive. Such actions include crew operations and commands. The SEC will issue cautions and warnings and possibly override crew inputs deemed unacceptable or improper in terms of overall station system safety. Since the crew retains the capability of direct modification of subsystem parameters, programming, and changeout or deactivation of devices and components, such SEC control need not represent a significant departure from the spirit of past caveats on manned space system operations.

2.4.2.6.1 Flight and Ground Crew Interface. The SEC must be designed with a degree of intelligence necessary for performing a wide range of supervisory tasks. This executive must accept ground-crew-initiated commands and begin the internal distribution process with a validation of the appropriateness and an analysis of the effects. These internal commands are the same type of commands issued by the executive in the autonomous mode of operation. Flight crew inputs can be accepted at this level of the architecture in the form of structured supervisory commands from the system manager. Data collected from the subsystems by the SEC can be displayed in a variety of formats for use by the crew in the decision process. An acceptable collection of responses or command types can be offered and crew selected for execution in this mode. The variety of crew control actions in the supervisory mode of control will be a subset of those which are available at the subsystem executive level. However, the analog devices and related supporting data displays at this level will not be present in an interaction with the SEC. Instead, the crew interface will be a terminal for display and digital input.

2.4.2.6.2 Fault Tolerance. Given its overall role in providing station system control and support, the SEC must be capable of correcting its own faults and preventing any cascading effects from reaching the various subsystems. As a consequence, the SEC requires significant hardware and software fault tolerance both internally in its computations and externally in its interfaces (see paragraph 2.3). This increase in fault tolerant capability at the executive levels over the capability exhibited at lower levels of the architecture is a characteristic of the heirarchical design. Such a hierarchy of fault tolerance can be achieved in part due to the reduction in data throughput at the higher levels of the architecture. This frees additional processing time to allow the necessary fault managing analyses to be performed in parallel with the supervisory, planning, and interface functions of the subsystem and station executives.

2.4.2.6.3 External Interfaces. The SEC plays a special role as the prime gateway to the users of the station system. Both flight and ground crew access the system principally through the command interfaces at the station command and control level. In the autonomous mode of operation, subsystems access other subsystems and services in the station system through the command and data interfaces of the SEC. This design feature of the hierarchical system provides a synchronizing tool for control of the distribution of processing in the system. The SEC can prioritize requests for service or action in the system, and resolve any conflicts due to the multiple uses of the station system.

2.4.2.6.4 Subsystem Interfaces. The SEC is the focal point of the command and data distribution process. This executive gathers data from the subsystems through a protected memory and data transmission interface. This data forms a resource of station system status information accessed by all subsystem executives. This data also becomes the principal source for displays at the consoles of the system manager, the flight crew member tasked with the supervisory control responsibility of the station system. The executive accepts plain text inputs from the system manager, formulates machine-readable commands and distributes these commands to the next lower level in the architecture. Commands transmitted from the ground crew through the communications and tracking subsystem are routed to this executive for validation, interpretation and distribution.

2.4.2.6.5 Interface Commands and Data Handling. Data is provided to the SEC regularly from the subsystem level executives through a data transmission bus. This bus is separate from the control interface of the SEC to the subsystem executives (see Figure 2-6). A simple direct memory access scheme could be utilized as the implementation of this data transfer bus. As such the subsystem executives and the SEC would then share a common memory. Alternately, to achieve a potentially higher level of fault protection capability, data may be collected from the subsystem executives in packets, then validated and stored by a separate database management function in the SEC. These data packets may contain routine status information as well as special subsystem data required for a system manager analysis display or part of an autonomous test and verification process. In the latter case this data can become input to the process which determines the status of the station system as a whole and as such forms the final layer of fault protection implemented in the system. The SEC autonomously issues commands to the subsystem executives through the intercom control bus. This bus serves to separate the data collection from the control function at this level of the architecture. Subsystems can initiate actions in other subsystems through this control interface bus connecting the subsystem executives. However, control by subsystems must be sanctioned by the SEC whenever such actions affect the station system or interfaces to the flight or ground crew.

2.4.2.6.6 Telemetry and Audit Trail. In support of the ground crew control function, the SEC provides audit trail data which traces the history of system actions. This audit trail is stored and readout from the SEC through a separate telemetry interface to the communications and tracking subsystem. Standard engineering telemetry is output from the SEC as well as from all subsystems, functions, and devices. This telemetry is handled through a potentially high-data-rate interface bus which is capable of providing the real-time data that comprise a telemetry function. As such, in this system which is partitioned by data rate, the telemetry bus becomes an underlying lower level of the architecture. The audit trail is accessible from the SEC as telemetry to the ground crew and, on request, as displayed data to the system manager. This data becomes a principal tool in the evaluation and diagnostic function provided by man in supervisory control of the station system. Consistent with the data bandwidth constraints, this audit trail is collected periodically by the subsystems as a report of unusual or anomalous behavior. Its transmission and storage then does not severely tax the data handling capability of the SEC and may be accommodated through the systems protected memory interface, as another type of specialized data packet (see paragraph 2.4.2.6 above).

2.5 ATTRIBUTES OF THE ARCHITECTURE

2.5.1 Distributed Computing

2.5.1.1 Introduction. The example hierarchical architecture utilizes a high degree of distributed computing to aid in achieving the objectives of man-interactive, fault-tolerant control of attitude, precision pointing, manipulators and navigation. The type of processors envisioned range from the simplest of microprocessors, in an interface to a pair of thrusters, to high precision computers performing computations of trajectory and orbit in floating point arithmetic, to a highly fault-tolerant computer with Hamming coded memory performing those executive tasks requiring reliable computing. All control and information interfaces are digitized with processing at all key stages of the formulation, conditioning and receipt of control commands and data.

2.5.1.2 Data Transmission and Communication. The interfaces in this architecture occur along a hierarchy of intercommunication busses. Each such bus is communication-bandwidth-limited with the most stringent speed requirement satisfied at the lowest levels of the architecture. By utilizing digital interfacing techniques, high-rate data output devices are supported through dedicated processors, using the intraprocessor bus as the mechanism for accepting and storing data at megahertz rates. By localizing this most communication-intensive throughput processing to a separate computer, the interprocessor transmission becomes a filtered, conditioned digital signal,

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tailored for further processing. In addition, the rate of transmission can be considerably less for this filtered output, so that conditioned versions of this output can be transmitted to more than one destination computer.

As functional constraints dictate, higher bandwidth communications amongst processors can be accommodated through the design of tightly coupled computing networks. These computers can be dedicated to a specific task such as data collectors, in the case of real-time image processing, or as data processors, in the development of a six-dimensional position and rate error signal from an advanced sensing or alignment system. The output, however, will appear to the receiving processor as though conditioned or collected from a single source. In fact a single processor in this highly coupled system may indeed be tasked solely with the job of performing the interface to the next higher level of processing. The rules of the hierarchical architecture dictate that the output at a given level conform to the bandwidth constraint of the next higher level of processing. In meeting this constraint, several different embedded processing architectural schemes may be employed. The hierarchy encourages unique solutions to throughput problems, while imposing system constraints which insure noninterference with other subsystem functions.

2.5.1.3 Interfaces Between Levels of the Architecture. A policy of non-interference implies a need for structured and selective interfaces to various levels of the architecture. A part of this structure is implemented through a two-level interface scheme. A functional implementation at a given level of the architecture can interface to at most the two nearest levels. As a consequence, interaction with the highest levels is forced to proceed through layers of protocols and interpretation, designed to validate both the request and response. This does not imply, that for example, a localized readout of a sensor signal output is prohibited. Rather, this readout can be collected and transmitted at a non-interference rate in parallel with the execution through the architecture of other subsystem functions. Similarly, priority commanding of equipment and other emergency activities is supported in this type of computing system design through digital implementations which allow for reprogramming, including the curtailing of the output of failed devices. The two-level interface scheme, when coupled with the distribution of a fault protection capability throughout the architecture, prevents a cascading effect which can lead to unrecoverable conditions.

2.5.1.4 Subsystem Interface Support at the Station Command and Control Level. At the highest levels of the system the greatest protection is present, insuring the validity of system actions. Due to the degree of data compression and preprocessing incorporated at the lower levels of the architecture, transmission bandwidth is much lower at the system level. As a result, subsystem to subsystem intercommunications can be hosted in a variety of computing architectures. Loosely coupled networks with message transmission systems to more tightly coupled systems having shared memory can support the intercommunication requirement. Consequently, a variety of processors can be incorporated into the performance of system functions. Highly fault tolerant computers can be used to implement system-level executive functions and provide in hardware and software the required bit error protection. Symbolic processors can be linked into the communication net at this level and provide off-line planning and analysis of system functions. Further, these specialized

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processors can be used to perform mission and crew scheduling, which are part of the station command control function yet are not real-time processing intensive. At the station command and control level such variety in processing can be supported with non-interference in routine system functional performance.

2.5.2 Control Function Hierarchy

2.5.2.1 Introduction. The nature of autonomous control dictates the need for hierarchical system implementations. Fully autonomous systems require the participation of system executive control of resources in the performance of major fault recovery operations and in the initiation of cooperative system-level functions which together achieve mission objectives. Appropriate system and subsystem partitioning of functional responsibility relieves the system executive of processing duties. Distributed computing supports the required throughput of the system through the simultaneous execution of functions. Yet, both mechanisms for the implementation of system functional capability accentuate the need for hierarchical design when requirements for autonomous operation are introduced. Subsystems must synchronize execution during autonomous fault recovery to achieve a 'fail operational' autonomy requirement. Subsystems must work together to perform maneuvers for orbit change or orbit maintenance. Processors must be provided structured access to system or subsystem data. In the event of failures, processors must be configured to maintain an acceptable level of operational capability and interface responsibility. Hierarchical control of these types of activities will insure execution which is consistent with and transparent to mission functions. Such control can apply the 'mission mode' filter to system actions: a filter which alters mission objectives to reflect changes in station capability or function.

2.5.2.2 Control of Interfaces. Hierarchical control architectures also afford the structure for outside interactions with autonomous systems. In the same fashion that executive control resources participate in the initiation or validation of system-level functions, ground station or flight crew control can be structured for easy and non-interruptive interactions with the system. This control in the form of commands can be distributed by the station and subsystem executives throughout the architecture along the normal digital interface paths. As such, these commands are acted upon by the subsystems, based in part on priority, but always under the constraint of appropriate system operation. Consequently, abnormal or unsafe configurations or operations in the system are avoided. Only valid system functions can be executed regardless of the source of initiation.

2.5.2.3 Validation at the Station Command and Control Level. Hierarchical executive control can contribute to the validation of outside interactions by exercising control both in rate and content of inputs. Ground station and man supervisory command and control occur through data inputs at the station command and control level of the architecture. Here the SEC can assign priorities, apply reasonableness checks, allocate processing resources such as access to the system interface bus and local support memory, and execute command and control consistent with the system design. Furthermore, if the SEC is designed in a structured manner, suggestive of an 'expert system', ground and flight crew command and control is in the form of a selection of alternatives prepared by the station executive. If a change in the baseline operational program of the system is determined by the crew, new programming can be introduced in the form of changes in control parameters at the station command and control level. These changes can further be validated within the design constraints of the system by the SEC in an interactive mode with ground or flight crew. Once so validated, the SEC introduces the changes into the system transparent to those functions unaffected by the changes, and consistent with the required level of system interaction. The result is a smooth transition between safe system configurations, necessary in a man-rated system.

2.5.2.4 Validation at the Subsystem Executive Level. A philosophy of validated interaction can be introduced at the next lower interface of flight crew to subsystem executives. Here analog controls allow `hands on` man inputs into a system. By design these inputs can be monitored and checked for consistency with the functioning of the system. Further since the SEC will be functioning during `hands on` interactive sessions, control over the effect of a crew input can be maintained, preventing possible unpredictable effects on other systems. The control hierarchy thus preserves the proper functioning of the system while it aids in flight and ground crew achievement of mission functions.

2.5.2.5 Fault Tolerance in the Hierarchy. The degree of control exercised by the station and subsystem executives in the architecture over outside interactions with the system is a part of the support for autonomous fault tolerance provided by the hierarchical design. Since these interactions proceed at rates which are lower than the typical execution of real-time subsystem functions, conventional techniques for achieving such control can be implemented at the station command and control and subsystem executive level. These techniques can include command sequence protection, reasonableness checks of commanded input, and bit error protection, all of which can be incorporated into the duty cycle of the functions of executive level services. At lower levels of the architecture, local throughput processing and data rate can increase. But because of the executive filter imposed on actions with system-wide impact, subsystem and local processing can be relatively self-contained and autonomous without the constraint of a system-wide monitoring task. Thus, implicit in the architectural design is a layering of fault tolerance. At the lowest layer, fault protection consists of the simplest of output reasonableness tests and internal device redundancy management. At higher levels of the architecture, tests of functionally redundant devices and activities proceed in parallel with routine maintenance of subsystem hardware. At the executive levels stringent hardware and software fault tolerance, coupled with comparison tests of actions versus design limitations, provides the final layer of fault protection which prevents fault propagation to other parts of the system.

This layered fault protection can also be viewed (and implemented) in the form of control loops. Each ascending layer or loop of protection proceeds at a lower rate of execution. At each layer up through the architecture more information from a wider variety of sources is factored into the tests which determine the health or state of a subsystem. Due to amount and varying character of such data, each layer of fault protection must process an increasingly complex protection function. So at the lowest layer of protection, local information which appears at a high rate is processed and utilized. At the highest layer, more information from many sources (but averaged and pre-processed to appear at a lower rate) is the input to the loop of protection. These loops of fault protection then are consistent with, and in fact determine, the type and style of processing. The highest rate loops require processing and data input consistent with the simplest of microprocessor implemented designs, which make use of the internal processor bus as the mechanism of interface. The slowest rate loops can benefit from the hardware fault protection implemented in highly fault tolerant computing architectures by receiving verified low rate data and processing complex protection schemes. The hierarchical architecture which partitions functions by bandwidth of data rate also partitions fault protection by bandwidth of execution and so achieves this layered effect.

2.5.3 Command and Engineering Data Handling

2.5.3.1 Hierarchy of Data Rates. Consistent with the hierarchy of control functions, the data and command architecture which supports autonomous operations must exhibit a partitioning by data rate and by command execution type. In a complex system such as the example of attitude control, precision pointing control, manipulator control, and navigation; a variety of data types and rates are determined by the levels of real-time control implemented in the system. High rate analog/digital data output from sensor and actuator devices is used in control laws designed to maintain attitude, point instruments or move manipulators. Intermediate rate data from these same devices is input to fault detection or performance analysis schemes which provide a portion of the implemented fault tolerance of the system. Lower rate data from the sensors is input to orbit determination processing which edits the data into an observable of orbit position. A selectable data rate outputs data from these devices for ground based telemetry or on-board diagnosis by ground or flight crew status monitoring. No one data rate or type can support all of the above functions, which are a part of the data handling job in the example system.

As a consequence, a set of pre-processing functions which transform digitized inputs from hardware into useable data to higher level functions is required to support the many uses of a single source of data. The implied data processing hierarchy, which controls and processes data for the next higher level of execution, is the support for the implementation of parallel functions in routine control and fault protection using near-term microprocessor technology. Further, this hierarchy supports a requirement of fault tolerance which is a part of autonomous operations in a man-rated system. By analyzing and checking the reasonableness of processed data, fault protection functions, which usually execute at rates much lower than that of real-time control functions, need not contend with critical system functions for processing resources. Since higher-level fault protection functions examine several sources of data as a means of validating a determination of the system state, pre-processing reduces the data bandwidth needed to provide this multi-source global view.

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2.5.3.2 Display and Analysis Data. Further processing of subsystem data is needed in support of the high level executive functions of the system and in support of the flight crew interface. Compressed data, which represents the status of several functions, provides a snap shot of subsystem processing and state observations used in health checking by subsystem executives. Selected packets of data displayed on a flight crew monitor, provide the capability for one or two crew member control of several complex subsystems. Depending on the mode of operation these packets may also provide a focused readout from a selected device for failure verification or diagnosis. To provide such a capability and yet support routine execution of subsystem functions, the data handling in the system must be flexible and programmable. A hierarchical system designed to separate high-speed data, associated with a telemetry function, from data necessary for real-time control and display can support these high level system data functions. Analogous to the preprocessing of data for subsystem level functions, further processing of data which results from subsystem function execution can provide the packets of data for display of subsystem status and analysis of functional performance. Since access to these packets is commanded through the highest levels of the architecture, the layered fault tolerance in the hierarchy provides a validated data input, while the reduced bandwidth of transmission at the higher levels allows processing time for the display and analysis functions without contention with critical subsystem functions. Bottlenecks can be avoided even in critical fault recovery situations without the implementation of high-speed data busses for these functions as a result of implicit data compression in the hierarchical system architecture.

2.5.3.3 Telemetry Data. High speed data transmissions may be needed to support a ground crew monitoring and analysis function. As implemented throughout the station system, a separate telemetry bus can be devised to supply the data for this function. Bit error protection need not be provided, since the received data will be processed and analyzed in off-line ground station facilities, where intermittent erroneous data will not induce inappropriate space system response. As a consequence standard telemetry interfaces can be designed and implemented without the protection required for interfaces at the control and command levels of the architecture. Further, the telemetry can be output asynchronous to the execution and data output rate of the subsystem devices and functions, as dictated by the priority assigned critical command and control functions for processing resources.

2.5.3.4 Audit Trail. The hierarchical system architecture can also support a ground crew analysis function by implementing a system-level audit trail function. Device and functions periodically record in packets of data the history of processes which monitor or respond to anomalous conditions in a subsystem. Treated as data packets for system display, these audit trail packets are transmitted to the system executive level for non-volatile storage and eventual readout on telemetry. By so creating such records the autonomous system can reduce the time spent by the ground or flight crew in the analysis of anomalous behavior. Furthermore, telemetry becomes a post-event debugging or analysis tool rather than the primary monitoring support function.

2.5.4 Man Supervisory Control

2.5.4.1 Flight Crew Supervisory Control. The example hierarchical system architecture allows two forms of flight crew interaction. The subsystem level

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'hands on' control is similar to current flight instrumented input into the control of the attitude and orbit of a manned spacecraft (Shuttle). In a manned station with a primary function of user payload servicing more supervisory forms of control must be utilized. Man supervisory control of the station system encompasses the role of a system manager who monitors and when necessary directs the performance of an autonomous subsystem. This subsystem executes a variety of housekeeping and maintenance functions autonomously. The subsystem reports the status of these activities periodically through displays to the system manager. This manager acts through a structured input language or through the selection of alternatives presented by the SEC. In keeping with the fault tolerance required of the system, crew inputs are validated before the SEC distributes or acts upon these commands.

2.5.4.2 Station Executive Controller Interaction in Supervisory Control. The role of an autonomous SEC is critical in enabling the above described supervisory control. This executive provides the mechanism for supervisory input through the interpretation of the input language and the presentation of data displayed in support of system status analysis. Data is gathered from the various subsystems and devices throughout the architecture in support of the display function. The various subsystem executives respond to requests for such input by transmitting data routinely gathered as a part of the support for station executive functions or by initiating selected data 'dwells' which provide detailed packets of information on the performance of subsystem functions and devices. Upon receipt of the data, the SEC stores, analyzes and displays in a variety of formats this accumulated data. The type of displays can be selected by the system manager. However, as part of the SEC analysis function, caution and warning displays are developed in the presence of failures or anomalous system behavior.

2.5.4.3 Supervisory Control Interface. The input from the system manager to the SEC can be structured through the use of a high-level command and control language. Such a language offers the manager a readable, natural language format for input. The SEC reforms this input into object level commands for executive analysis. Depending on the sophistication in the design of this executive, these commands may be in the form of high-level commands for execution by subsystem(s) executives. Before the object level commands are distributed; the SEC validates the input as a part of the fault tolerant design. This validation can take the form of simple reasonableness checks, error checking of an input on menu displays, or verification with models of anticipated system performance. In this latter case, some form of knowledge-based capability incorporated in the SEC can evaluate the input versus constraints such as safety and expected mission functions planned for the period of command execution. In an interactive mode, the system manager and the SEC can together formulate and distribute the commands which accomplish the objective.

2.5.4.4 Cooperative Control. While such command generation, validation and distribution is taking place, the SEC with the support of the various subsystems nominally controls those functions unaffected by the commanded input. The commands are distributed and acted upon in a systematic manner by the subsystems, so that during the transition and new modes of operation a consistent system configuration is preserved. Further, due to this non-interference philosophy of command distribution and response from the SEC through the architecture, ground crew commands can be accepted and acted upon in parallel with the crew inputs. The SEC evaluates the reasonableness of the commands from flight or ground crew in the same manner, i.e., based on the objectives of the mission and constraints of safety of the flight crew and station. The hierarchical architecture can allow such simultaneous commanding due to the design which makes the station executive the source of distribution and validation of all commands.

2.5.4.5 Override Control in the Supervisory Mode. In the case of unpredicted events or unplanned activities the SEC interface allows a man override command capability. When built into the high-level command and control interface language, override parameters or data inputs can be accepted in natural language form. When accepted by the SEC, a more sophisticated form of validation must be performed to achieve fault tolerance. The override input requires analysis or comparison with models of performance of devices and functions affected by the input. These models may contain limits or other evaluation parameters which define performance in various modes of system or subsystem operation. To deviate from these limits requires an override by the flight or ground crew. Once so changed, the SEC can accept and act upon the new input. The interaction between man and machine here has the form of programming, in a high level computing language, a computer which has a 'smart' interpreter or compiler.

2.5.4.6 Critical Commanding. In any mode of supervisory control, the SEC must support a capability for 'go/no go' of critical functions. Certain safety critical conditions require crew (either flight or ground) authority before SEC actions are initiated. In this role the SEC can support the crew generated decision by providing the data requested or needed, and perhaps by evaluating alternatives and presenting options for action. In a similar manner, by filling the role of on-board manager during unmanned autonomous periods, the SEC is designed to simplify the type of ground input required to control the station system. This input can be supervisory 'go/no go' commanding, which utilizes the same high-level control language of the on board, manned supervisory control interface. The extent of ground crew supervisory support can be reduced during these autonomous periods and localized to control of the most critical cases of troubleshooting station system-level anomalous events.

2.5.5 Man 'Hands On' Control

2.5.5.1 Flight Crew 'Hands On' Control. The traditional support for crew input in a manned spacecraft involves analog mechanisms such as joysticks, potentiometers, strip charts, and selected digital displays, all of which are derived from aircraft cockpit designs. A space station which will incorporate payload control and support manipulator control will add to the above arrays of monitors and sensors which simulate or display payload or effector response. The hierarchical architecture supports these quasi-real-time inputs from the flight crew at the subsystem executive level of the architecture. These inputs must conform however to the constraints of safety, fault tolerance and mission objectives. As a consequence, the subsystem executives are similarly tasked, as is the SEC under man supervisory control, with a validation function in support of the acceptance of crew 'hands on' inputs.

2.5.5.2 Subsystem Executive Interface and Validation. The subsystem executive prepares data collected from its various subsystem functions and devices for display to the crew in the 'hands on' mode of control. Some of the data can be scaled and formatted for 'heads up' displays. Other data can be selected by the crew for digital readout. Other display formats may involve direct metering of devices or proportional feedback to a joystick or other device which simulates a physical state. This output to the crew is under the subsystem executive control and so provides the mechanism for system validation of any resultant crew input. The scale of the analog input devices can be designed based on the performance limits of the functions or devices involved. The input then can be transformed or conditioned by the subsystem executive based on the scale of the device. So for example, the crew input on a joystick, which controls attitude during a maneuver sequence, can be conditioned by the attitude control subsystem executive so that the controlling thrusters are pulsed in a manner proportional to the degree of deviation of the joystick from the upright position and to the constraints of safe operation of the thrusters. Depending on the sophistication of the attitude control executive, the operation of the joystick in the above example can be further constrained by the design and performance limits of the station as a whole. So no rates beyond a safe limiting value could be imparted to the station as a result of the operation of the thrusters by virtue of an erroneous input from the joystick.

2.5.5.3 System Interaction in the 'Hands On' Mode. The addition of caution and warning lights or displays by the subsystem executive in this mode of crew control can aid in the validation and verification process. Due to the position of this input support in the architecture, the crew 'hands on' control mode can be provided in concert with the autonomous control of other subsystems. At the highest level in the architecture, the SEC views crew control as the exercise of one function of the complex station system, subject to the same requirements for safety and mission imposed on system functions in the purely autonomous mode of operation. As a result, the SEC can issue caution and warnings to the flight crew in the man supervisory mode of control and to the ground crew concerning the status of the system. In the presence of nominal performance, the SEC supported by subsystem executives can maintain and operate devices and perform functions that are unaffected by the action of the crew in the 'hands on' control mode of a particular subsystem. Given the hierarchy of control, functions and devices can be simultaneously controlled by the ground crew, by the flight crew in the supervisory mode, and by the flight crew in 'hands on' modes of control. The SEC, being the coordinator of the system, can sort and prioritize requests for service from multiple sources and accept commands for station level actions from the crew. This executive can perform such control since a part of its functioning during all modes of station operation is to allocate control resources. The variety of manned inputs, once translated by executive processing in the hierarchical architecture into object level commands, appear as system-level requests for control and are so treated. Commands at this level of definition are then distributed by the subsystem executives for execution at the subsystem and device function levels.

2.5.5.4 Override Control. The limits for and the interpretation of the inputs from analog or other crew `hands on` devices are maintained by the subsystem executives and are translated into digitized form. In a programmed mode in support of man supervisory control, the SEC can accept input commands from the crew to override or modify these limits or interpretations of the analog device controllers. In fact, depending on the type of function controlled, these interpretation parameters can be autonomously modified as a part of the routine maintenance or performance analysis of a fault tolerant system. Once so modified, the input analog devices can change performance characteristics. However, the input from these devices remains constrained by the limits of performance of other devices and functions in the subsystem which cooperate in achieving the control effect.

2.5.5.5 Service Functions. The validation and verification of crew inputs in the `hands on` control mode does not affect or restrict other types of crew servicing or controlling actions on the station. Beyond noting the effects, the station or subsystem executives do not enter into the physical replacement of faulty equipment or the changeout of payload instruments or other devices on the station. The reprogrammability of the analog devices for `hands on` control supports changeout by allowing a recasting of the functions of the devices. The same joystick control used in pointing a telescope for example can be used to point an antenna as part of a technology development test. A digital control capability allows such reprogramming and redefinition.

2.5.6 Growth Potential

2.5.6.1 Requirement for Growth. A distributed computing architecture with digitized, standardized interfaces can adapt to new technology in microprocessors and memory through changeout which conforms to the constraints in the interfaces of the original system. However, unless such computing is designed in an architecture consistent with the function of the system, it will be difficult to add functional capability or respond to new methods of computing. To provide for growth the system must allow the introduction of alternatives in technology and function in a test or development mode. This provides a validation procedure commensurate with the eventual use of the test article. Further the system must be flexible and adapt to the presence of new subsystems, functions and devices with minimal disturbance of or to the original system. No one system architecture can absorb unrestrained growth. However, to the extent of anticipated use and growth of the station command and control capability, the hierarchical system architecture provides attractive mechanisms for expansion.

2.5.6.2 Support for Growth. By partitioning functions in the hierarchy by data rate of transmission, the architecture supports the early introduction of new computing technologies. New computing devices can be slaved to existing equipment in the implementation. Since moderate data rates exist at all but the local device level, these new devices can be exercised in a focused testing mode which does not have to account for support of rapid throughput in the system. Further, tests of these devices can be performed at the station system level with man in supervisory control. As described above, packetized data collected at the subsystem device or function level can be transmitted upon request to the station command and control level as a part of a `dwell` function. The information or readout of the new device in a test of

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performance can be monitored using this capability. A comparison with response in the existing system can also be done in virtual real-time using this feature, since packets of data although collected in parallel from two or more different devices will be transmitted sequentially to the SEC for reformatting as comparison graphs, etc. This aids the post mortem test analysis of the system manager or mission specialist in the crew.

2.5.6.3 Support for Expert Systems. The above described test procedures may be the mechanism for introducing a full scale expert system into the command and control system. In an initial implementation such a system may be slaved to perform planning and off-line analysis of system state for the SEC. If implemented using a symbolic processor, the expert system could not support high rate data or provide real-time control output. By virtue of the partitioned hierarchy, the expert system need not assume a key system role in its introductory phase. Instead, the validity of its results can be compared in operational test situations, with customary performance of the system. Further, in initial use, the expert system can be restricted to the generation of high-level objectives or commands for system-level action. This mode of functioning is not unlike that of a system manager in a supervisory mode of operation. Its inputs are treated at the subsystem or station command and control level as another source subject to error and requiring validation by the system fault protection. This example illustrates the flexibility and transparency to system actions that autonomy can provide. In a layered fault protection design, intrinsic to a hierarchical system, error cannot proliferate and cause secondary effects, even if such error is introduced in a development mode of operation.

2.5.6.4 New Subsystems. When introducing new functions into the command and control architecture, the data throughput required for the function should be considered. This throughput determines one parameter in the eventual position of this function in the architecture. The requirement for support from functions or devices already in the system can determine the topology of interface for the function. Due to the distribution of processing in the system and preprocessing/compression of outputs at each level, support for the new function may involve a simple rerouting of data in the architecture. However, if the processing required and the topology of interface are at odds, a new intermediate level of interface can be introduced for the new function. Since within any given level of the architecture a variety of computing architectures can be supported, provided interface constraints are met, adding pre- or post-processors to an implementation of the function cannot introduce computing bottlenecks or other throughput anomalies.

2.5.6.5 Unmanned Platform Commonality. Since the hierarchical architecture is an inherent characteristic of autonomous control, an early capability of an implemented system in the space station will be support for unmanned autonomous operations. The example system contains a man interactive overlay and support which aid in the convenient and efficient use of the system by flight and ground crews. If the flight crew interactive overlay was not present, the result would be a design which could support a system such as the command and control of an unmanned platform. The parameters and some of the functions of the described hierarchy could change in such a setting, however the support for growth to full autonomous capability would remain. This multi-mission adaptability can favorably affect the cost of a multi-element space system as the space station is envisioned, providing a recurring use for a single developed capability.

2.6 TECHNOLOGY TREES

The following charts (Figures 2-7a through d) relate specific technology topics to the example autonomous control architecture. The architecture has not been developed to requirements in sufficient detail to make it worthwhile to link it to specific objectives and targets or to identify them as "needs" for the architecture. Consequently, the charts relate the relevance of the specific technology topics to the level of control in the architecture. A detailed design at an architecture level might be implemented without the application of a specific technology, but the availability of the technology would provide positive support to the effort.

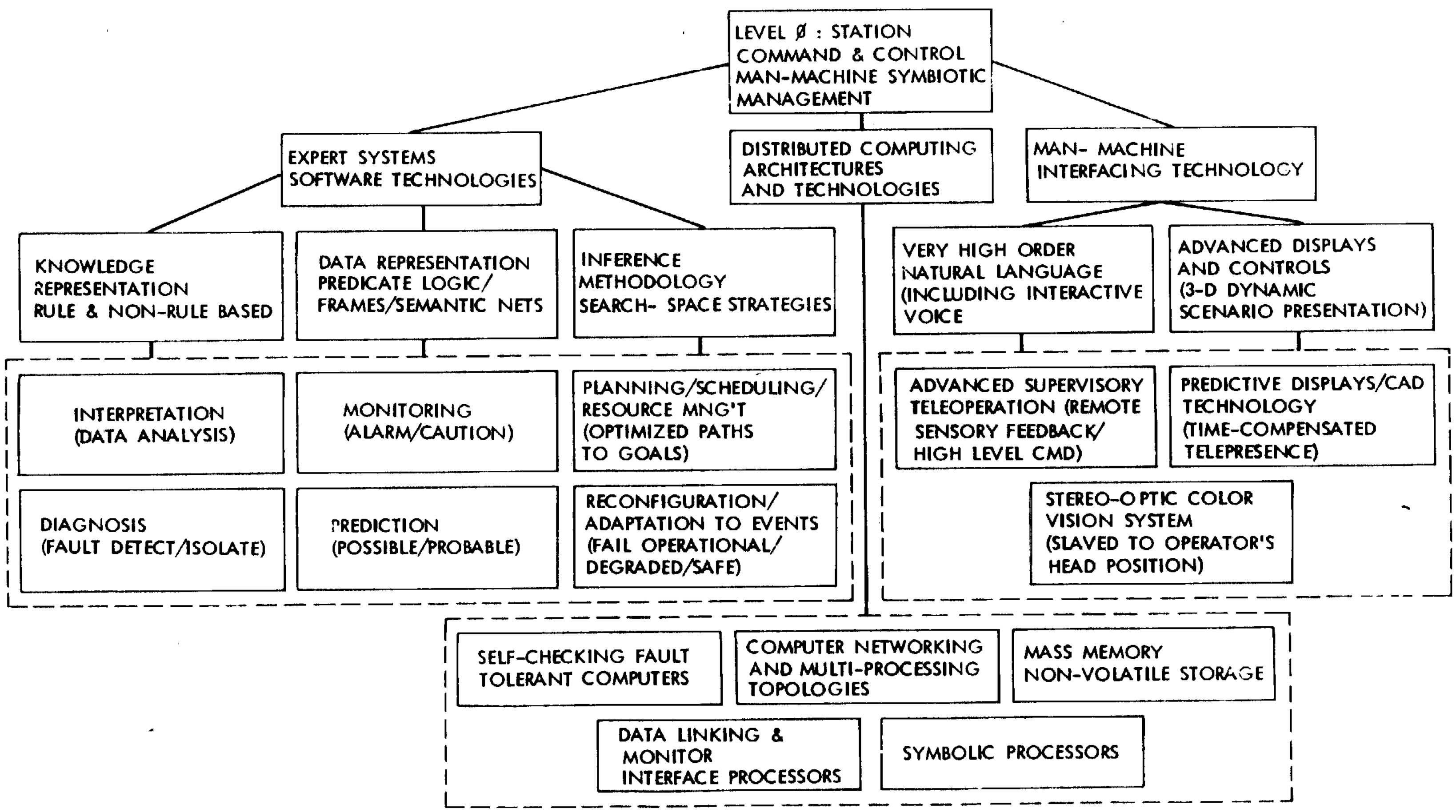

Figure 2-7a. Technology Tree for Space Station Autonomy Command and Control Architecture, Level 0: Station Command and Control, Man-Machine Symbiotic Management

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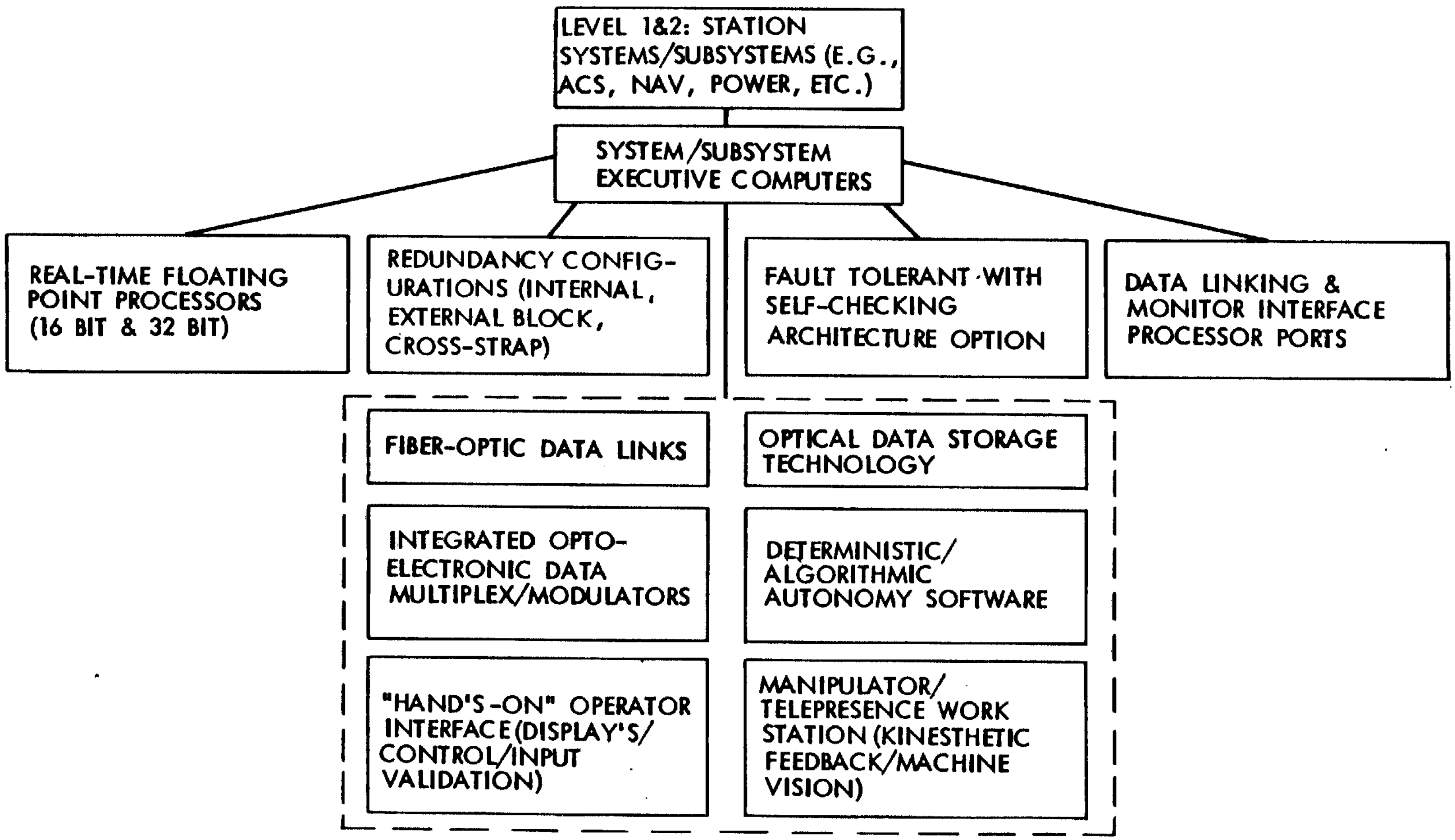

Figure 2-7b. Technology Tree for Space Station Autonomy Command and Control Architecture, (cont), Levels 1 & 2: Station Systems/Subsystems (e.g. ACS, NAV, Power, etc)

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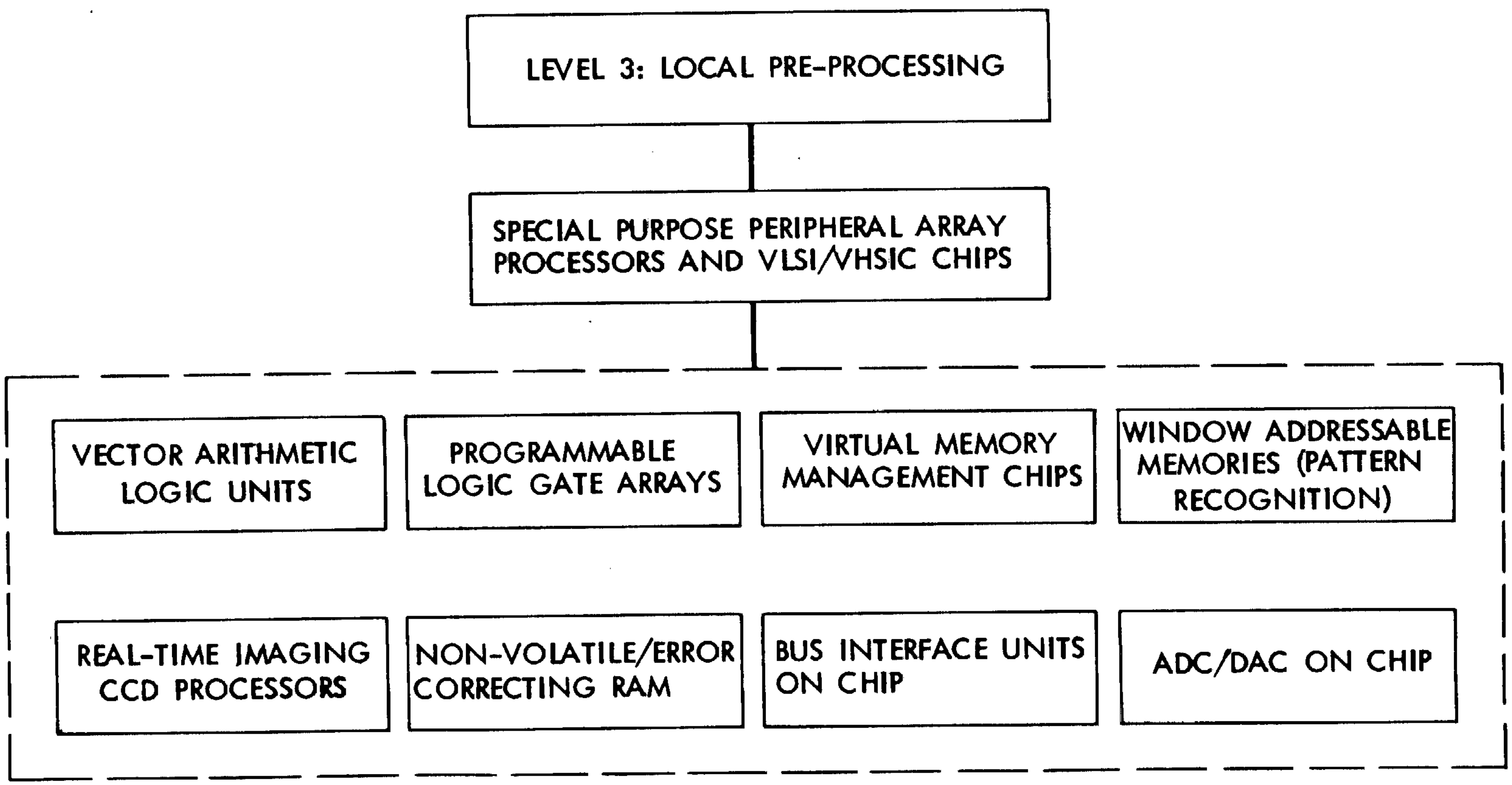

Figure 2-7c. Technology Tree for Space Station Autonomy Command and Control Architecture, (cont), Level 3: Local Pre-Processing

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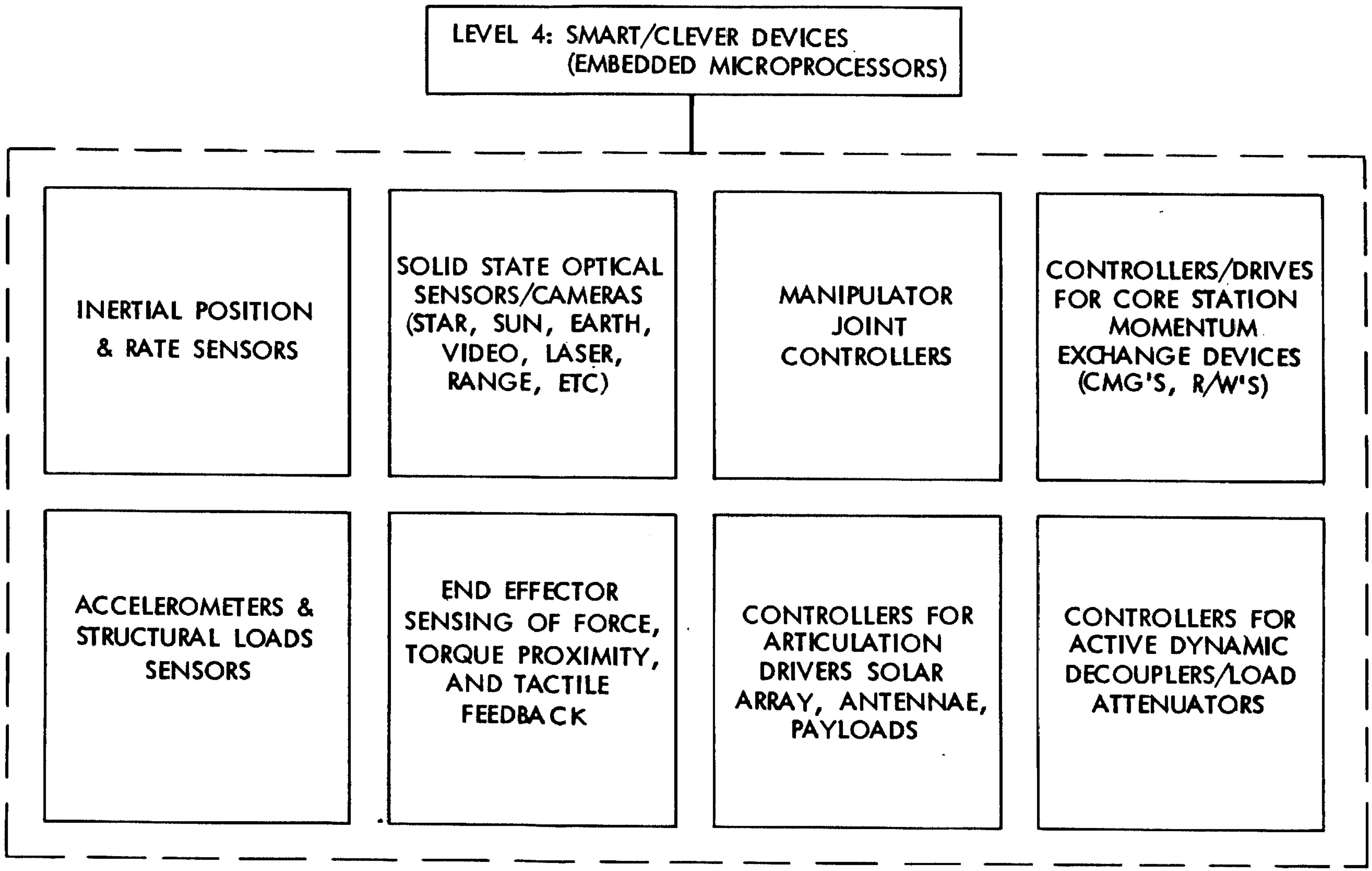

Figure 2-7d. Technology Tree for Space Station Autonomy Command and Control Architecture, (cont), Level 4: Smart/Clever Devices (Embedded Microprocessors)

PART 3

TECHNOLOGY NEEDS EVALUATION

3.1 INTRODUCTION

The approach to the evaluation of the technology plans in the FY'84 PASO was to review the status of the technology currently under development, compare that with what will be required to support an autonomous space station, and identify any technology areas that are not currently being supported.

The initial source of technology needs was derived from the work that was done earlier in the year (prior to the development of a candidate architecture) where subsystem and system experts, experienced in the application of autonomy to unmanned spacecraft, expressed their views relative to the technology development required to provide autonomy for a manned space station. The results of that activity are described in detail in Appendix A. All the "needed" technologies have been excerpted from Appendix A and listed in Table 3-1.

The evaluation of the technology plans started with a review of the FY'84 PASO. Those PASO targets which appeared to have an impact on the technology required for support of space station autonomy were selected for further study. These were categorized with consideration given to the amount of influence the proposed technology would have on the achievement of autonomy and to the level of the system functional hierarchy where the technology would be most applicable. The following three categories were identified:

a. System wide application to Autonomous Control: Technology is so fundamental that application would be throughout the Space Station design.

b. Subsystem Function Specific: Technology is primarily relevant to a specific subsystem function.

c. Potential for Implementation Option: Technologies that may have application throughout the Space Station and provide implementation alternatives or enhancements.

The evaluation of PASO targets against technology "needs" will be presented as follows:

a. <u>The identification of the new targets needed to support the technology development not being supported by the current PASO (paragraph 3.2).</u>

Technologies that were identified as "needed" but are apparently not supported by the current PASO targets are identified, categorized, and described.

b. A discussion of the selected current PASO targets (paragraph 3.3).

From the PASO, targets that appear to have an impact on the implementation of autonomy have been selected. Each target is categorized as described above and recommendations are given for improving the alignment of the target with the technology needs.

c. A table summarizing PASO target characteristics (paragraph 3.4).

Table 3-2 provides in summary form the PASO Target description, the category (System, Subsystem, or Option) to which the target has been assigned, PASO Targets that appear to be related, the identification of the testbed to which the target technology would be most relevant, and the period during which the target technology is being worked.

d. A discussion of interrelated PASO Targets (paragraph 3.5).

For those PASO targets that appear to be related to one another, a brief discussion of the relationships is provided.

e. The identification of relationships between the technology needs and the PASO targets (paragraph 3.6).

Table 3-3 provides a cross-reference between "needed" technologies that appear to be supported by the current PASO targets. Table 3-4 provides a listing of PASO targets and the corresponding "needed" technologies.

3.2 TECHNOLOGY NEEDS NOT SUPPORTED BY PASO TARGETS

The following technology areas grouped by category appear to be unsupported by the current set of PASO Targets. Within the Subsystem Function Specific category the technologies are further grouped by technical discipline.

3.2.1 System Wide Application

a. Operating System Software. The space station requires an "operating system" to provide control interfaces between manual and machine autonomous operating features. This operating system must provide a control language to support the human command interface and the supporting software to implement commands and directives from the operators, control the execution of software in the system, provide utility functions to the operators, and report on the status and operation of the system. The commonality of the operator control requirements for all mission phases (subsystem integration test, system integration test, flight operations, inflight integration test and validation, etc.) requires that this operating system be developed in advance of flight operations needs. The early development of this operating system and its control language will provide a common standard for control and operation that will unify the efforts of many diverse contractors working at the subsystem level. Test procedures written in a common language syntax simplify understanding of the procedures by integrators and provide a direct point of departure for development of flight operations procedures.

Table 3-1. Needed System Technologies

Technology Code	Technology Title
	Propulsion
1A	Develop an autonomous PROP control system to gather, process and store sensor data for system performance and health determination.
1B	Develop the architecture and the interfaces of autonomous PROP and the space station system executive.
1C	Develop an integrated sensing and processing technique for inflight determination of propellant mass and pressurant mass remaining.
1D	Develop an integrated sensing and processing technique for inflight detection, identification location, and isolation of pressurant or propellant leakage.
1E	Develop the sensing and processing techniques autonomous inflight determination of thruster performance and health status.
1F	Develop the sensing and processing techniques for autonomous inflight servicing/refueling of the space station and its peripherals.
1G	Develop an autonomous PROP system with interfaces to autonomous NAV and ACS for maneuver planning support and thruster performance assessment.
1H	Develop an autonomous PROP system with ACS interface for thruster inflight calibration.
1I	Develop the architecture and the interface for PROP system interactive operations with the space station crew.
	Communication and Tracking System Technologies
2A	Develop algorithms and hardware for implementation of configuration control for the complex network of space station communication links.
2B	Develop the architecture and the control, feed and operational techniques for an affordable antenna system for the space station communication links.
2C	Develop the necessary techniques (i.e., identification, compensation, etc.) for simultaneous operation of the many space station communication links in an RFI environment (including space station generated RFI).

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Table 3-1. Needed System Technologies (cont'd)

Technology Code	Technology Title
	Communication and Tracking System Technologies (cont'd)
2D	Develop the architecture and necessary techniques to operate the complex and unencumbered intra-vehicular voice nets for the space station.
2E	Develop implementation methods for monitoring, self-test, malfunction detection and trend analysis.
2F	Develop an RF and/or optical docking and rendezvous sensor system.
2G	Develop a lightweight, space-qualified radar system for surveillance and traffic control.
	Power System Technologies
4A	State of charge indicator/adaptive charging.
4B	Compact, nonintrusive, low mass voltage, current, and switch position sensors.
4C	High-voltage, high-power dc switches and circuit breakers.
	Data Management System Technologies
5A	Software development aids.
5B	Man/machine interfaces.
5C	Custom VLSI manufacturing/testing.
5D	Non-volatile solid state memory.
5E	Fiber optics.
5F	Fault tolerant microcomputers.
5G	Radiation hard microprocessors.
5H	Flight quality, high density bulk storage.
5I	System executive and data system architectures.
5J	Special purpose algorithm development.
5K	Robotics/teleoperators/artificial intelligence/expert systems.

Table 3-1. Needed System Technologies (cont'd)

Technology Code	Technology Title
	Data Management System Technologies (cont'd)
5L	Automated sequence/command generation.
5M	Automated position/time generation.
5N	Hardware design aids.
	Guidance and Control
7A	Develop an interactive autonomous ACS with an interface to an autonomous NAV system on board the space station.
7B	Develop and interactive autonomous ACS with an interface to an autonomous Traffic Control system on board the space station.
7C	Develop flight qualify radiation tolerant computers and memories (both volatile and non-volatile).
7D	Develop network or distributed system data distribution and executive control for space station application.
7E	Develop the architecture of and space station the interfaces among an autonomous ACS, a space station system executive, and the crew.
7F	Develop an integrated sensing and processing technique for in-flight system identification of space station dynamics, flexible body characteristics, and control performance.
7G	Develop space station distributed and adaptive control techniques for the suppression, decoupling, and isolation of dynamically interactive elements (e.g., modules, payloads, attached structures).
7H	Develop an integrated precision pointing system for small payload control on the space station.
7I	Develop the sensing and integrated control technology for the crew and manipulators or teleoperators on board the space station.
7J	Develop the optical and inertial sensors and effector technology for the support of attitude and pointing control.
7K	Develop an automatic command sequence generation capability.

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Table 3-1. Needed System Technologies (cont'd)

Technology Code	Technology Title
	Guidance and Control (cont'd)
7L	Develop Bite for ACS devices and the interface with autonomous fault protection and maintenance control.
7M	Develop the technology for autonomous adjustment of control laws, and as adaptive, supervisory fault management system.
	Thermal Control
8A	Develop an interactive, autonomous thermal control subsystem.
8B	Develop an environment sensing pointable radiator system.
8C	Develop onboard trend analysis and performance prediction capability.
	Navigation
9A	Onboard navigation.
9B	Crew-interactive navigation system.

A key element in the development of this "operating system" will be the identification and definition of the parameters for the control of autonomous subsystems. These parameters include the priorities assigned to subsystem functions in operational scenarios, the mechanisms for fault recovery which preserve a consistent system configuration, and the criteria for validation of gound system and crew inputs to the real-time autonomous operation of the system. A set of generic tools must be developed which lead to the definition of these parameters in a complex space system. Such tools will provide the means for implementations of the "operating system" to any space station or unmanned space system concept. Through the identification of these tools and the process for their application, the mechanism for adapting control parameters to system growth or unplanned system conditions becomes apparent. Any development of an automated means, such as an expert system, for this adaption of control parameters must be derived from the experience gained through the application of the generic tools. To a lesser extent these same tools will apply in the development of interactive, autonomous subsystems, which must also orchestrate a variety of routine and fault-induced operations of control and computing resources. In this sense then each subsystem area, in addition to the spacecraft system as a whole, should be addressed in a technology development program which results in options for the realization of autonomous control.

The importance of the "operating system" issue cannot be over emphasized. Current technology efforts address hardware and applications software at lower levels of control, but there is no formal technology effort underway to create this operating system software. Such software will be critical to the control and operations of the space station.

b. Validation of System Design Concepts. The candidate control architecture described in Part 2 is an extrapolation of work performed for spacecraft systems on the basis of experience with planetary spacecraft design. The concept is considered valid, but no attempt has been made to build even a simplified version of the upper levels of the control hierarchy. Many detailed trades are possible to allocate functions among levels of the hierarchy and to distribute functions to specific computing resources. A "testbed" activity for system autonomous control needs to be defined and funded to allow these issues to be addressed and to assess the best approach to the fundamental trade-offs.

3.2.2 Potential for Implementation Options

The use of built-in test equipment (BITE) is an important aspect of an autonomous system design. The need for BITE has been noted in some subsystems, but it is important that a BITE concept and implementation philosophy be developed for application to an autonomous system composed of numerous autonomous subsystems.

On-board trend analyses will be required if the station is to be autonomous for a significant interval of time. Trend analyses will be needed to support autonomous fault management, maintenance, navigation, and a variety of other subsystem functions. One obvious example of the need for trend analyses capability is in the area of thermal load prediction, but other areas will also need to make predictions based on observed trends. There is a need to identify those areas where trend analysis is required to support each of the autonomous activities. Subsequent to the identification of these areas, the requirements that each area places on the trend analysis capability need to be defined.

3.2.3 Subsystem Function Specific

A review of the 52 technologies suggested for development by subsystem engineers, and documented in Appendix A, led to the identification of the following subsystem areas which appear to be unsupported by the FY`84 PASO.

a. Propulsion: Sensing and processing techniques (with acceptable resource requirements - mass, volume, power) to provide in-flight detection, location, and isolation of pressurant and/or propellant leaks.

Sensing and processing techniques (with acceptable resource requirements - mass, volume, power) to provide in-flight determination of thruster performance and health status.

b. Communications: Because of the anticipated complexity of managing the numerous communication links with multiple transmission paths and all operating in an RFI environment, technology is needed to support an early development of software and hardware which implements configuration control of the space station communication networks.

There is also a need for a light weight space qualified radar system for surveillance and traffic control.

c. Navigation: Autonomous stationkeeping will require an autonomous navigation system for establishing and maintaining the station orbit. The development of a limited capability autonomous navigation system is currently being pursued by the Air Force in the Autonomous Spacecraft Program (ASP) at JPL. Autonomous navigation will require development of both software (programs) and hardware (fault tolerant processors and data sensors).

d. Traffic Control: The potential for a large number of coorbiting free-flying spacecraft will require a traffic control system whose functions are to:

1) Place coorbiters in parking orbits remote from the space station.

2) Maintain the parking orbits in the presence of atmospheric and other disturbances.

3) Monitor the parking orbits to avoid collisions of coorbiters with one another and with the space station. Take corrective actions in case safe minimum separations cannot be ensured. Corrective actions include issuing appropriate warnings to the flight crew and/or ground controllers.

4) Retrieve coorbiters from parking orbits to the vicinity of the space station.

5) Provide automatic and/or crew-supervised rendezvous and docking with coorbiters.

e. Guidance and Control. Technologies should be developed for space station application which provide options for autonomous adjustment of control laws and control parameters, and which enable the development of adaptive and supervisory fault management systems. Such technologies as expert systems, could apply system-wide support to control problems or fault recovery scenarios. Furthermore, the development of such technologies would aid in solving the control and fault management problem in station growth concepts. However, in order to provide the required capability, these technologies must be developed for real-time control applications.

3.3 PROGRAMS AND SPECIFIC OBJECTIVES ASSESSMENT FOR AUTONOMY TECHNOLOGY

ASST activity for the last third of FY 1983 has concentrated on defining an example Autonomous Command and Control System Architecture for the core space station and assessing the relationship between this concept and the current OAST technology plans defined in the PASO for FY 1984. The assessment involves identification of those current plan objectives and targets that are related to the implementation of the architecture concept and the identification of additional objectives and targets that are related but not currently in the plans.

The example autonomous control system architecture has a hierarchical distribution of control authority. Control resources, whether computers or processors, may exist at system level, subsystem level, or be embedded in a sensor or lower-level element of a subsystem. The hierarchical control structure is fundamental to the autonomous control of a large, complex system. Further references to "system level" or "subsystem level" are with respect to the control hierarchy defined in the example architecture concept described in paragraph 2.4.2

The objectives/targets that have been identified as autonomy-related are divided into three categories by impact upon the architecture concept, and suggested additions or changes to the targets are proposed to more directly relate them to the concept. The three categories relate the objectives/targets to autonomy as (1) system wide fundamental needs, (2) subsystem level specific, or (3) significant design/implementation options without regard to level of implementation.

a. System Wide Needs: These items relate directly to the provision of autonomous control for the core station example concept and are applicable to autonomous control of mission related functions as well. Some items are fundamental to the provision of system level autonomous control and most are applicable to control at the subsystem level and below as well.

b. Subsystem Level Specific: These items address needs for autonomous control of a specific functional subsystem. While the work is fundamental to the particular subsystem, it will probably influence autonomy in other subsystems only through functional interface specifications.

c. Significant Autonomy Design/Implementation Options: These items address capability that is important to improve or enhance the performance of autonomous control at the system or subsystem level. The basic implementation of the control may be accomplished by alternate means, but the particular item may significantly affect the ability of the implementation to meet design requirements.

The following assessments have been developed from the descriptions of specific objectives and targets defined in the FY 1984 PASO document. Individual Research and Technology Objective Plans (RTOP) have not yet been examined to assess their relevance to the example autonomous control architecture concept.

3.3.1 System Wide Needs

3.3.1.1 Computer Science - Computer Science and Electronics R&T.

OAST Sponsor. Larsen

Target 54-5B. Develop and validate network operating system constructs and user dialog interfaces for unifying distributed heterogeneous systems for space applications by the end of FY 1984.

> Recommendation: Adapt work to address systems that implement a hierarchical control structure and validate with scenarios of autonomous system operation.

Target 54-5C. Develop custom LSI/VLSI testability requirements and design methods for the self-checking computer and communications modules by the end of FY 1984.

> Recommendation: Consider a plan to assess the inpact of utilizing symbol-oriented logic machines with building block modules in addition to the current digital logic machines.

Target 54-5G. Develop circuit design principles, techniques, and testability measures for fault-tolerant, space-qualifiable LSI/VLSI computing architectures by the end of FY 1985.

> Recommendation: Develop design for self-test and failure recovery at the hardware level for interface units to memory and communications buses. Consider need for fault-tolerant design of controllers for special mass-storage devices (i.e. bubble memory, optical disk recorders, etc.) Assess the impact of data bus communications rate upon the design of a fault-tolerant bus interface module.

Targets 54:5H. Develop an initial set of verified software specification metrics by the end of FY 1986 and a full set of verified software management and measurement tools by the end of FY 1987.

> Recommendation: Add consideration of special attributes of fault-tolerant software systems and knowledge-based designs. Consider the use of metrics and tools associated with the ADA language and software development environment.

3.3.1.2 Automation - Computer Science and Electronics R&T.

OAST Sponsor. Larsen

Target 54-6B. Demonstrate feasibility of knowledge-based approach for automating major fault analysis functions by the end of FY 1984.

> Recommendation: Consider design provisions for 'learning' optimized systems, place special emphasis on real-time operation in an automated, closed-loop operating mode, and address differences between this and a man interactive mode.

Target 54-6D. Develop expert system technology capability and validate in a NASA context by the end of FY 1984.

> Recommendation: Plan to address the following points:

a. Use of expert systems in a real-time environment including time-domain and hierarchical partitioning of functions, application as part of a closed loop control system, and implementation with digital vs symbol logic based machines.

b. Design of a natural language interface that is utilized as a Test and Operations Control Language for human interface in both integration test and flight operations environments.

c. Fault-tolerant hardware and software in an expert system design.

d. Design of interfacing expert subsystems.

e. Programming language requirements for operational use.

f. Use with a real-time operation scheduler with mission phase/ operation mode dependant constraint checking.

3.3.1.3 Human Factors - Controls and Human Factors R&T.

OAST Sponsor. Montemerlo

Target 57-2D. Develop human/computer interface design guidelines for computer systems to be used in space operations and maintenance - FY 1986.

Recommendation: Direct guidelines to manned supervisory control of space station system. Consider man-supervised autonomous system in real-time operation and near real-time planning modes. Address input validation and constraint checking/monitoring requirements. Link these guidelines to Test and Operations Control Language discussed in 54-6 Expert Systems Technology Development target.

Target 57-2E. Develop technology for using advanced display and command technology for improving space transportation and platform crew stations - FY 1986.

Recommendation: Adapt to multi-function/multi-mode crew control stations that can allow supervisory or detailed manual control of core system/subsystem functions and monitoring/control of mission functions (payload, OTV, etc.).

3.3.1.4 Data Systems - Space Data and Communications R&T.

OAST Sponsor. Wallgren

Target 58-1F. Develop a network simulation capability and evaluate network designs for Space Station - FY 1985.

Recommendation: Evaluate systems that provide data communications in a hierarchical control system architecture. Evaluate in simulated autonomous control/operation scenarios.

3.3.1.5 Systems Analysis - Platform Systems R&T.

OAST Sponsor. Carlisle

Target 64-1A. Develop automation assessment methodology and define hierarchical systems automation and technology requirements for automated subsystem control/management - FY 1984.

Recommendation: Develop methodology from systems perspective of system level control of interacting subsystems co-operating in the performance of system functions. Identify technology requirements for high-value generic application, specific subsystem autonomous operation applications, and performance enhancing design options.

Target 64-1B. Exercise space station models to determine system performance and sensitivity to key configuration parameters and interaction with subsystem combinations of technology capability - FY 1984.

Recommendation: Models should allow simulation of autonomous operation with varying degrees of man interactions (supervision, control, etc.) and ground control, with attendant impact upon communications link requirements, crew productivity, and ground system size and capability. It should be possible to evaluate partitioning of control between ground and on-board resources by analyzing the real-time nature of the control requirements.

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Target 64-1D. Define requirements for automated systems status monitoring and integrated subsystem techniques for fault detection, isolation, and recovery - FY 1984.

> Recommendation: Address man supervisory control options, and consider the phasing of implementation using knowledge-based techniques developed in the 54-6 Automation target.

Target 64-1F. Define requirements for artificial intelligence techniques as an enabling technology for system/subsystem autonomous operation - FY 1984.

> Recommendation: Consider both man-interactive and machine autonomous implementation requirements. Address the issues identified above in 54-6 Automation target. Define system executive function requirements, considering ease of changes/updates, `learning` from changing conditions in operation, evolvability of system design, and testing/validation of AI functions in an operational setting.

Target 64-1G. Develop interface concepts, standards, and protocols applicable to advanced space data systems - FY 1984.

> Recommendation: Interface concepts should address hierarchical command and control architectures. Appropriate human factors and automation targets of 54-6 and 57-2 should be considered. The Test and Operations Control Language concept and its relationship to the interface concepts, standards, and protocols should receive particular attention.

Target 64-1K. Develop and evaluate data management system architecture concepts that would integrate space station facility and user requirements - FY 1985.

> Recommendation: Develop separate user data service architecture apart from core station system. Integrate core system/subsystem data with user data output for downlink to ground.

Target 64-1L. Define system/subsystem interface architecture requirements to optimize evolutionary growth - FY 1985.

> Recommendation: Consider evolution effects on performance of autonomous control hierarchy. Consider techniques of design to allow addition of new capabilities with minimum impact on baseline design and minimize associated test and validation activities.

Target 64-1M. Define requirements for crew "safe haven" retreat and transfer to rescue vehicle - FY 1985.

> Recommendation: Consider multiple-failure tolerant system design and definition of levels of `degraded` system performance. Consider role of fault-tolerant executive in control of system and need for access to executive control in "safe haven".

Target 64-1N. Determine space station automation requirements.

Recommendation: Consider man as a system supervisor and as a subsystem operator as two different requirements generation options. Evaluate space/ground partitioning of functions in the context of time domain of operations (i.e. long term activities versus real-time control/supervision).

Target 64-1O. Develop a system-level functional simulation to examine effects of subsystem performance, interaction, and failure modes, and identify critical system and subsystem input/output parameters and levels - FY 1986

Recommendation: Consider simulation in a man integrated setting with scenario of man as a supervisor of system operation. Coordinate with other simulations of data management, automation modeling.

3.3.1.6 Operations - Platform Systems R&T.

OAST Sponsor. Carlisle

Target 64-2F. Establish allocation of functions to man and machine that optimize overall operational efficiency and utilization of the crew - FY 1985.

Recommendation: Consider machine operation augmented with planning tools and high-level manned input. Concept should be adaptable to inclusion of knowledge based planners and command interpreters. Overall operations scenario should include autonomous real-time system control.

3.3.2 Subsystem Level Specific

3.3.2.1 Automation - Computer Science and Electronics R&T.

OAST Sponsor. Larsen

Target 54-6L. Develop and demonstrate automation techniques for control of the operation of spacecraft subsystems using an advanced life support system as a demonstration pilot plant by the end of FY 1985.

Recommendation: Analyze the techniques and characterize as generic automation/autonomy related or life support subsystem specific. Life support specific techniques could be further divided into those that support techniques common to life support (i.e. atmosphere pressure and composition monitoring) and those that are specific to a particular design characteristic of the baseline design. Generic techniques for the subsystem might be derived from automation/autonomy techniques used for the Power subsystem control target of 55-7 and System Fault Management and Power subsystem control targets of 64-1. Furnish example autonomous control architecture and evaluate for partitioning of functions among system executive control resource, subsystem executive resource, and distributed resources within subsystem elements. Evaluate techniques for both normal and fault-tolerant operation.

3.3.2.2 Power Systems Management and Distribution.

OAST Sponsor. Hudson

Target 55-7F. Autonomous Power Subsystem Management

Recommendation: Analyze work into generic and subsystem specific components as described for 54-6 Life Support subsystem target.

3.3.2.3 Advanced Controls and Guidance Concepts - Controls and Human Factors R&T.

OAST Sponsor. Dahlgren

Target 57-3A. Complete development and testing of advanced long-life angular sensor and inertial measuring system concepts for potential use in spacecraft guidance systems or large space structure control systems - FY 1984.

Recommendation: Examine sensor concepts for those that are applicable to autonomous control by virtue of simplifying control requirements or providing "smart sensor" design to off-load subsystem level processing for normal operation or fault detection and correction.

3.3.2.4 Systems Analysis - Platform Systems R&T.

OAST Sponsor. Carlisle

Target 64-1I. Advance the technology needed for automation of the space station power subsystem FY 1984-1987.

Recommendation: Coordinate with work in 55-7 target. Supply system autonomous control architecture concept to contractor and address partitioning of power subsystem control functions among a system level executive control resource, a power subsystem executive, and various distributed control resources within the elements of the subsystem. Examine the subsystem control concept for applicability of normal and fault-tolerant control implementations developed under generic system autonomy work in 64-1.

3.3.2.5 Operations - Platform Systems R&T.

OAST Sponsor. Carlisle

Target 64-2C. Develop and validate simulation capability to assess man-machine interface and human performance in teleoperated and robotic systems - FY 1984.

Recommendation: Coordinate with Control & Display target of Human Factors 57-2. Consider utilization of autonomous/automatic system models from simulation targets in 58-1 and 64-1. If models are not applicable, common guidelines/assumptions should be considered for control characteristics and interfaces with supporting subsystems.

Target 64-2E. Develop simulations for rendezvous and docking maneuvers and define requirements for caution and warning/collision avoidance FY 1985.

> Recommendation: Estimate software sizing and computational requirements for techniques to allow assessment of impact for on-board implementation. Consider respective roles of active and passive partners in the maneuvers to allow partitioning of tasks in the manner that best utilizes existing capabilities (i.e. Shuttle navigation capability) and allows appropriate allocation of functions to the core space station navigation and traffic control facility.

3.3.3 Significant Autonomy Design/Implementation Options

3.3.3.1 Analysis and Synthesis - Materials and Structures R&T.

OAST Sponsor. Venneri

Target 53-5D. Develop, by the end of FY 1985, an integrated analysis/synthesis capability which addresses the dynamic behavior of large aerospace structures under mechanical and thermal excitations, including structures/controls interactions.

> Recommendation: Consider use of techniques in this area for predicting or monitoring the dynamics of space station structures during attitude/orbit maneuvers or for deformation of structure and displacement of payloads or structural elements. Possible impact upon autonomous control of structural dynamics of core structure.

3.3.3.2 Automation - Computer Science and Electronics R&T.

OAST Sponsor. Larsen

Target 54-6C. Develop the fundamental technology needed for machine vision systems with target body tracking over a noisy background by the end of FY 1984.

> Recommendation: Adapt for remote supervision of EVA and proximity operations.

Target 54-6E. Develop tools and techniques for automating elements of the spacecraft uplink process by the end of FY 1984.

> Recommendation: Adapt for commanding of free flyers and platforms from space station system control. Link effort to development of Test and Operations Control Language and overall core station control architecture implementation of command functions.

Target 54-6F. Demonstrate feasibility of improving mission operations productivity and effectiveness by application of expert systems technology in a control center environment by the end of FY 1984.

Recommendation: Adapt techniques of real-time and near real-time scheduling, planning, and validation and constraint checking of command inputs to on-board applications. Link this effort with the development of Test and Operations Control Language and man-machine interface work of other targets.

Target 54-6J. Develop and demonstrate AI techniques for information extraction from image data by the end of FY 1985.

Recommendation: Adapt to integrated machine vision for supervision of EVA, proximity operations, etc.

Target 54-6K. Develop the technology for generalized extraction of low-level image features at video frame rates by the end of FY 1985.

Recommendation: Adapt to integrated machine vision for supervision of EVA, proximity operations, etc.

Target 54-6M. Develop an architectural design for a space-borne symbolic processor by the end of FY 1985.

Recommendation: Include in the design, considerations for fault-tolerance and error recovery at the hardware level (with software/firmware support). Add considerations of memory efficiency and throughput needed for real-time support of an on-board closed-loop control system.

Target 54-6N. Demonstrate algorithms for automated planning and optimization of manipulator trajectories subject to environmental, physical, and energy constraints by the end of FY 1986.

Recommendation: Consider man supervisory control of manipulators and integration with machine vision and autonomous verification of system operation. Consider fault-tolerance and error recovery in design of software algorithms for implementation.

Target 54-60. Develop the technology base for an experimental telepresence system for space manipulation tasks which outperforms direct human manipulation by the end of FY 1987.

Recommendation: Consider man supervisory control of manipulators and integration with machine vision and autonomous verification of system operation. Consider fault-tolerance and error recovery in design of software algorithms for implementation.

3.3.3.3 Human Factors - Controls and Human Factors R&T.

OAST Sponsor. Montemerlo

Target 57-2A. Establish state of the art, technology needs, and capabilities to research and develop design and evaluation tools and techniques for space human factors discipline applications......

Recommendation: Consider impact of man supervisory control of large autonomous systems, including the need for presentation of status and control information and the constraint checking of manual inputs.

3.3.3.4 Data Systems - Space Data and Communications R&T.

OAST Sponsor. Wallgren

Target 58-1B. Continue development of high-density, wide temperature range magnetic bubble memory devices using ion implant technology - FY 1984.

Recommendation: Consider impact of sequential bulk memory on system data access and throughput requirements. Good potential for backup storage of large quantities of software and data base information in on-board control systems.

Target 58-1C. Develop an optical disk recorder capable of ingesting and retrieving data at 50 million bits per second, and storing 10 to the 11th power bits per disk - FY 1984.

Recommendation: Consider random access optical disk technology for system data storage.

Target 58-1G. Complete and evaluate ADA in a test environment - FY 1985.

Recommendation: Consider ADA as an implementation language for the system executive, general control system software, Test and Operations Control Language, and future knowledge-based or expert systems.

Target 58-1I. Develop very high-speed integrated circuit technology system for use as the general-purpose onboard space station core data processing unit with insertion in the test bed in FY 1987 - FY 1987.

Recommendation: Consider use in access of system executive of a hierarchical control architecture to high-speed user data services. Consider in microprocessor and building block design for implementation of fault-tolerant self-checking computers.

Target 58-1J. Develop high-speed optical data bus network architecture, components, optical nodes, and system consistent with space station data rates and processors for insertion in the test bed in 1987 - FY 1987.

Recommendation: Consider integration of optical bus for user data services with low-speed system command and control data bus.

3.3.3.5 Systems Analysis - Spacecraft Systems R&T.

OAST Sponsor. Couch

Target 62-2D. Complete LEO/GEO spacecraft subsystem technology assessment and requirements - FY 1984.

Recommendation: Consider autonomous hierarchical control system with resources distributed to subsystems. Consider interface with station core navigation and traffic control subsystem.

Target 62-2I. Provide spacecraft analytical tool to quantitatively study subsystem interactions - FY 1985.

Recommendation: Develop tool capability to test and evaluate subsystem level autonomous control and interface with a system autonomous executive control resource.

3.3.3.6 Systems Analysis - Platform Systems R&T.

OAST Sponsor. Carlisle

Target 64-1C. Formulate methodology and techniques to develop a phased system and subsystem simulation/emulation capability - FY 1984.

Recommendation: Consider requirements for structured validation of system and subsystem interaction in a hierarchical autonomous control system. Develop tool capability to evaluate knowledge-based systems.

Target 64-1E. Perform system and discipline analysis/trade studies to develop generic requirements for platform systems - FY 1984.

Recommendation: Consider partitioning of functional control amoung system executive, subsystem executive, and subsystem element control resources in a hierarchical control structure.

3.3.3.7 Operations - Platform Systems R&T.

OAST Sponsor. Carlisle

Target 64-2D. Define space and ground logistics, maintenance, and servicing requirements for platforms, stations, and other free flying systems in close orbital proximity - FY 1984.

Recommendation: Evaluate autonomous control of maintenance functions as related to methodology for station core. Consider man supervision or monitoring of these functions.

3.4 PASO TARGET SUMMARY

Table 3-2 provides a summary overview of the PASO Target assessment. The data shown consists of the following:

a. The first column lists the code number that has been assigned to the specific PASO Target as used in the Technology Assessment Paragraph 3.3.

b. The second column contains a description of the PASO Target as extracted from the PASO. Descriptions have been truncated from the full text of the PASO in order to keep the table reasonably compact.

c. The third column lists the category to which the Target has been assigned. The categories include "System" which designates Targets that address technology that is fundamental to autonomy and would find application throughout the space station, "Subsystem" which designates targets addressing technology that may have application primarily to a specific subsystem area, and "Option" which address technologies that may be applicable throughout the space station but will provide either implementation alternatives or performance enhancements.

d. The fourth column lists the number assigned to Targets that appear to be related in as much as they address similar technology areas. The relationship between Targets may be generic in as much as they address technologies in a generic area or the relationship may be specific if Targets address a specific technology.

e. The fifth column identifies the testbed that would most probably be associated with the Target technology. The technology may aid in the development of the testbed or the testbed may be used to evaluate the technology for its appropriateness to flight. The testbed abbreviations used in the table are:

AC Attitude Control

DM Data Management

EC Environmental Control/Regenerative Life Support

EP Electrical Power

OP On-board Propulsion

TM Thermal Management

SO Space Operations Mechanisms

f. The last four columns are used to show the planned time when the PASO Target is scheduled to be active. An "x" in the column indicates that activity is scheduled for that fiscal year. FY'84, FY'85, FY'86, and FY'87 are shown.

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Table 3-2. PASO Target Summary

PASO	PASO Target Description	Category	Related Targets	Testbed	Schedule 84	Schedule 85	Schedule 86	Schedule 87
53-5D	Develop an integrated analysis/synthesis capability which addresses the dynamic behavior of large aerospace structures under	Option		AC	x	x		
54-5B	Develop and validate network operating system constructs and user dialogue interfaces for unifying distributed heterogeneous systems for space application	System		DM	x			
54-5C	Develop custom LSI/VLSI testability requirements and design methods for the self-checking computer and communications modules	System	54-5G		x			
54-5G	Develop circuit design principles, techniques, and testability measures for fault-tolerant, space-qualifiable LSI/VLSI computing architectures	System	54-5C	DM	x	x		
54-5H	Develop an initial set of verified software specification metrics by the end of FY86 and a full set of software management and measurement tools by 87	System		DM	x	x	x	x
54-6B	Demonstrate feasibility of knowledge-based approach for automating major fault analysis functions	System	54-6D 64-1F 54-6F	DM	x			
54-6C	Develop the fundamental technology needed for machine vision systems with target body tracking over a noisy background	Option	54-6J 54-6K		x			
54-6D	Develop expert system technology capability and validate in a NASA context	System	54-6B 54-6F	DM	x			

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Table 3-2. PASO Target Summary (cont'd)

PASO	PASO Target Description	Category	Related Targets	Testbed	Schedule 84	Schedule 85	Schedule 86	Schedule 87
54-6E	Develop tools and techniques for automating elements of the spacecraft uplink process	Option		DM	x			
54-6F	Demonstrate feasibility of improving mission operations productivity and effectiveness by application of expert systems technology in a control center	Option	54-6B 54-6D 64-1F	DM	x			
54-6J	Develop and demonstrate AI techniques for information extraction from image data	Option	54-6C 54-6K	AC	x	x		
54-6K	Develop the technology for generalized extraction of low-level image features at video frame rates	Option	54-6C 54-6J	AC	x	x		
54-6L	Develop and demonstrate automation techniques for control of the operation of spacecraft subsystems using an advanced life support system............	Subsystem	55-7 64-1	EC	x	x		
54-6M	Develop an architectural design for a space borne symbolic processor	Option		DM	x	x		
54-6N	Demonstrate algorithms for automated planning and optimization of manipulator trajectories subject to environmental, physical, and energy constraints	Option	64-2C 54-60	AC	x	x	x	
54-60	Develop the technology base for an experimental telepresence system for space manipulation tasks which outperforms direct human manipulation	Option	54-6N 64-2C	AC	x	x	x	x
55-7F	Complete technology readiness of an autonomously managed power subsystem	Subsystem	64-1I	EP	x	x	x	

Table 3-2. PASO Target Summary (cont'd)

PASO	PASO Target Description	Category	Related Targets	Testbed	Schedule 84	85	86	87
57-2A	Establish state of the art technology needs and capabilities to research and develop design and evaluation tools and techniques for space human ...	Option		DM	x			
57-2D	Develop human/computer interface design guidelines for computer systems to be used in space operations and maintenance	System	64-1G	DM	x	x	x	
57-2E	Develop technology for using advanced display and command technology for improving space transportation and platform crew stations	System		DM	x	x	x	
57-3A	Complete development and testing of advanced long-life angular sensor and inertial measuring system concepts for potential use in spacecraft guidance	Subsystem		AC	x			
58-1B	Continue development of high-density,wide temperature range magnetic bubble memory devices using ion implant technology	Option	58-1C	DM	x			
58-1C	Develop an optical disk recorder capable of ingesting and retrieving data at 50 million bits/second, and storing 10 to the 11th power bits per disk	Option	58-1B	DM	x			
58-1F	Develop a network simulation capability and evaluate network designs for space station	System		DM	x	x		
58-1G	Complete and evaluate ADA in a test environment	Option		DM	x	x		
58-1I	Develop a very high-speed integrated circuit technology system for use as the general-purpose onboard space station core data processing unit	Option		DM	x	x	x	x
58-1J	Develop high-speed optical data bus network architecture, components, optical nodes, and system consistent with space station data rates/processors	Option		DM	x	x	x	x

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Table 3-2. PASO Target Summary (cont'd)

PASO	PASO Target Description	Category	Related Targets	Testbed	Schedule 84	Schedule 85	Schedule 86	Schedule 87
62-2D	Complete LEO/GEO spacecraft subsystem technology assessment and requirements	Option			x			
62-2I	Provide spacecraft analytical tools to quantitatively study subsystem interactions	Option		DM	x	x		
64-1A	Develop automation assessment methodology and define hierarchical system automation and technology requirements for automated subsystem control/management	System		DM	x			
64-1B	Exercise space station models to determine system performance and sensitivity to key configuration parameters and interactions with subsystem	System			x			
64-1C	Formulate methodology and techniques to develop a phased system and subsystem simulation/emulation capability	Option	64-2C 64-1O		x			
64-1D	Define requirements for automated systems status monitoring and integrated subsystem techniques for fault detection, isolation, and recovery	System	64-1N	DM	x			
64-1E	Perform system and discipline analysis/trade studies to develop generic requirements for platform systems	Option			x			
64-1F	Define requirements for artificial inelligence techniques as an enabling technology for system/subsystem autonomous operation	System	54-6B 54-6D 54-6F		x			
64-1G	Develop interface concepts, standards, and protocols applicable to advanced space data systems	System	57-2D	DM	x			
64-1I	Advance the technology needed for automation of the space station power subsystem	Subsystem	55-7F		x	x	x	x
64-1K	Develop and evaluate data management system architecture concepts that would integrate space station facility and user requirements	System		DM	x	x		

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Table 3-2. PASO Target Summary (cont'd)

PASO	PASO Target Description	Category	Related Targets	Testbed	Schedule 84	Schedule 85	Schedule 86	Schedule 87
64-1L	Define system/subsystem interface architecture requirements to optimize evolutionary growth	System		DM	x	x		
64-1M	Define requirements for crew "safe haven" retreat and transfer to rescue vehicle	System			x	x		
64-1N	Determine space station automation requirements	System	64-1D	DM	x	x	x	
64-1O	Develop a system-level functional simulation to examine effects of subsystem performance, interaction, and failure modes, and identify critical	System	64-1C 64-2C		x	x	x	
64-2C	Develop and validate simulation capability to assess man-machine interface and human performance in teleoperated and robotic systems	Subsystem	54-6N 54-6O 64-1C		x			
64-2D	Define space and ground logistics, maintenance, and servicing requirements for platforms, station, and free flying systems in close orbital proximity	Option			x			
64-2E	Develop simulations for rendezvous and docking maneuvers and define requirements for caution and warning/collision avoidance	Subsystem		AC	x	x		
64-2F	Establish allocation of functions to man and machine that optimize overall operational efficiency and utilization of the crew	System		DM	x	x		

3.5 INTERRELATED PASO TARGETS

PASO targets which seem to be related to one another are grouped together and identified by the same number and description used previously in Table 3-2. Following the grouping is a brief discussion of the apparent relationship between members of the group.

a. 54-5C Develop custom LSI/VLSI testability requirements and design methods for the self-checking computer and communications modules.
   54-5G Develop circuit design principles, techniques, and testability measures for fault-tolerant, space-qualifiable LSI/VLSI computing architectures.

Both of the above targets address the development of LSI/VLSI. One appears to be at the circuit level and the other at the module level; therefore, they should be supportive of one another.

b. 55-7F Complete technology readiness of autonomously managed power subsystem.
   64-1I Advance the technology needed for automation of the space station power subsystem.

The above two targets appear to have essentially the same objective.

c. 57-2D Develop human/computer interface design guidelines for computer systems to be used in space operations and maintenance.
   64-1G Develop interface concepts, standards, and protocols applicable to advanced space data systems.

Both of the above targets address interfaces. The first is concerned only with the human/computer interface. However, this interface is only one of the interfaces involved, and all interfaces should be considered as a set. These targets could support one another in areas that are not currently being considered (e.g. manned supervisory control of space station).

d. 58-1B Continue development of high-density, wide temperature range magnetic bubble memory devices using ion implant technology.
   58-1C Develop an optical disk recorder capable of ingesting and retrieving data at 50 million bits/second, and storing 10 to the 11th power bits per disk.

The above targets are related to bulk data storage. The high data rates are not required for autonomous control, but the large storage capacity is certainly desirable. These targets are not supportive of each other, but do address generic approaches to the target.

e. 64-1D Define requirements for automated systems status monitoring and integrated subsystem techniques for fault detection, isolation, and recovery.
   64-1N Determine space station automation requirements.

Target 64-1D appears to be an element of 64-1N, but the level of detail is insufficient to determine this. Perhaps 64-1N addresses high level generic requirements and 64-1D addresses more detailed requirements. If this is the case, 64-1N should provide the framework for 64-1D, except 64-1D is scheduled for completion in FY84 and 64-1N is scheduled for completion in FY86. These two may not be too supportive of each other, as presently organized.

f. 54-6B Demonstrate feasibility of knowledge-based approach for automating major fault analysis functions.
54-6D Develop expert system technology capability and validate in a NASA context.
54-6F Demonstrate feasibility of improving mission operations productivity and effectiveness by application of expert systems technology in a control center.
64-1F Define requirements for artificial intelligence techniques as an enabling technology for system/subsystem autonomous operation.

The above targets all address topics in the AI field. There would appear to be a range of capabilities under investigation. This is appropriate since technology advancement should continue during the life of the space station and may be incorporated as it becomes available. These targets should all be supportive of one another as the data obtained from one should have relevance to the others.

g. 54-6C Develop the fundamental technology needed for machine vision systems with target body tracking over a noisy background.
54-6J Develop and demonstrate AI techniques for information extraction from image data.
54-6K Develop the technology for generalized extraction of low-level image features at video frame rates.

The above targets address the topic of generation or use of video data. It would appear that generic techniques are being considered, and they may be supportive of each other or they may be redundant.

h. 54-6N Demonstrate algorithms for automated planning and optimization of manipulator trajectories subject to environmental, physical, and energy constraints.
54-6O Develop the technology base for an experimental telepresence system for space manipulation tasks which outperforms direct human manipulation.
64-2C Develop and validate simulation capability to assess man-machine interface and human performance in teleoperated and robotic systems.

The above targets are related through the planned space-based use of manipulation. Automated control may differ from teleoperation, but there should be enough similarities to make them supportive of one another.

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i. 64-1C Formulate methodology and techniques to develop a phased system and subsystem simulation/emulation capability.
64-10 Develop a system-level functional simulation to examine effects of subsystem performance, interaction, and failure modes, and identify critical ......
64-2C Develop and validate simulation capability to assess man-machine interface and human performance in teleoperated and robotic systems.

The above targets represent different aspects and levels of simulation. The results of one should certainly be considered in the others. They should be supportive of each other since they do focus on different aspects of simulation.

3.6 PASO TARGETS RELATED TO TECHNOLOGY NEEDS

Early in the year, a number of "Technology Needs" were identified (see Appendix A). Table 3-3 is presented in order to provide a quick reference between these technology needs and the current PASO Targets. Technologies identified by a technology code number from Table 3-1 and Appendix A are listed along the ordinate and PASO Targets identified by code numbers as shown in Table 3-2 are listed on the abscissa. An intersection identified by "*" indicates which specific technologies are being supported by each PASO Target.

Table 3-4 provides the next lower level of detail relating the technology needs to the PASO Targets. For more details of the Technology needs see Appendix A. The first two columns in Table 3-4 list the technology code number and title of the technologies that are supported by the PASO Target listed in the first two columns. Some PASO Targets support multiple technologies and for some PASO Targets corresponding technology needs have not yet been identified. In some cases, such as life support systems, technologies were probably not identified since the primary experience and expertise of the subsystem and system engineers who defined the technology needs were in the area of unmanned space systems. In addition, their focus was on the technologies that would provide increases in capability or reduction in resource requirements for the implementation of autonomy. Where PASO Targets exist without defined technology needs an open item is considered to exist; therefore, the entry of NA (Not Available) is used for the technology code number and "TO BE DEFINED" is entered for the technology title. In some cases technology needs are defined and no corresponding PASO Target is identified; these technology needs are summarized in paragraph 3.2

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Table 3-3. Reference Guide to Technologies Supported by PASO Targets

PASO TARGET CODE NUMBERS

TECHNOLOGY CODE NUMBERS	54-5B	54-5C	54-5G	54-5H	54-6B	54-6D	57-2D	57-2E	58-1F	64-1A	64-1B	64-1D	64-1F	64-1G	64-1K	64-1L	64-1M	64-1N	64-1O	64-2F	54-6L	55-7F	57-3A	64-1I	64-2C	64-2E	53-5D	54-6C	54-6E	54-6F	54-6J	54-6K	54-6M	54-6N	54-6O	57-2A	58-1B	58-1C	58-1G	58-1I	58-1J	62-2D	62-2I	64-1C	64-1E	64-2D
1B	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1I	-	-	-	-	-	-	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2E	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	*	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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4C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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54-5B 54-5C 54-5G 54-5H 54-6B 54-6D 57-2D 57-2E 58-1F 64-1A 64-1B 64-1D 64-1F 64-1G 64-1K 64-1L 64-1M 64-1N 64-1O 64-2F 54-6L 55-7F 57-3A 64-1I 64-2C 64-2E 53-5D 54-6C 54-6E 54-6F 54-6J 54-6K 54-6M 54-6N 54-6O 57-2A 58-1B 58-1C 58-1G 58-1I 58-1J 62-2D 62-2I 64-1C 64-1E 64-2D

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Table 3-4. PASO Versus Technology

PASO	PASO Target Description	No.	Technology Title
53-5D	Develop an integrated analysis/synthesis capability which addresses the dynamic behavior of large aerospace structures under	7F	Develop an integrated sensing and processing technique for in-flight system identification of station dynamics, flexible body characteristics, and ...
		7G	Develop distributed and adaptive control techniques for the suppression, decoupling and isolation of dynamically interactive elements
54-5B	Develop and validate network operating system constructs and user dialogue interfaces for unifying distributed heterogeneous systems for space application	7D	Develop network of distributed systems data distribution and executive control
54-5C	Develop custom LSI/VLSI testability requirements and design methods for the self-checking computer and communications modules	5C	Custom VLSI manufacturing/test
		5F	Fault tolerant microcomputers
54-5G	Develop circuit design principles, technique, and testability measures for fault-tolerant, space-qualifiable LSI/VLSI computing architectures	5C	Custom VLSI manufacturing/test
		5F	Fault tolerant microcomputers
54-5H	Develop an initial set of verified software specification metrics by the end of FY86 and a full set of software management and measurement tools by 87	5A	Software development aids
54-6B	Demonstrate feasibility of knowledge-based approach for automating major fault analysis functions	5K	Robotics/Teleoperator/Artificial intelligence/Expert systems

Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
54-6C	Develop the fundamental technology needed for machine vision systems with target body tracking over a noisy background	7J	Develop the optical and inertial sensors, and effector technology for the support of attitude and pointing control
		2F	Develop an RF and/or optical docking and rendezvous sensor system
54-6D	Develop expert system technology capability and validate in a NASA context	5K	Robotics/Teleoperator/Artificial intelligence/Expert systems
54-6E	Develop tools and techniques for automating elements of the spacecraft uplink process	7K	Develop an automatic command sequence generation capability
		5L	Automated Sequence/Command generation
54-6F	Demonstrate feasibility of improving mission operations productivity and effectiveness by application of expert systems technology in a control center	5K	Robotics/Teleoperator/Artificial intelligence/Expert systems
54-6J	Develop and demonstrate AI techniques for information extraction from image data	7J	Develop the optical and inertial sensors, and effector technology for the support of attitude and pointing control
		2F	Develop an RF and/or optical docking and rendezvous sensor system
54-6K	Develop the technology for generalized extraction of low-level image features at video frame rates	7J	Develop the optical and inertial sensors, and effector technology for the support of attitude and pointing control
		2F	Develop an RF and/or optical docking and rendezvous sensor system
54-6L	Develop and demonstrate automation techniques for control or the operation of spacecraft subsystems using an advanced life support system............	NA	TO BE DEFINED

Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
54-6M	Develop an architectural design for a space borne symbolic processor	NA	TO BE DEFINED
54-6N	Demonstrate algorithms for automated planning and optimization of manipulator trajectories subject to environmental, physical, and energy constraints	5J	Special purpose algorithm development
		7I	Develop the sensing and integrated control technology for the crew and manipulators or teleoperators on board
54-60	Develop the technology base for an experimental telepresence system for space manipulation tasks which outperforms direct human manipulation	5K	Robotics/Teleoperator/Artificial intelligence/Expert systems
		7I	Develop the sensing and integrated control technology for the crew and manipulators or teleoperators on board
55-7F	Complete technology readiness of an autonomously managed power subsystem	4A	State of charge Indicator/adaptive charging
		4B	Compact nonintrusive, low mass, voltage and current and switch position sensors
		4C	High voltage, high power DC switches and circuit breakers
57-2A	Establish state of the art, technology needs, and capabilities to research and develop design and evaluation tools and techniques for space human ...	NA	TO BE DEFINED
57-2D	Develop human/computer interface design guidelines for computer systems to be used in space operations and maintenance	1I	Develop the architecture and the interface for PROP system interactive operations with the space station crew

Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
		5B	Man/Machine interfaces
		7E	Develop the architecture of and the interface among an autonomous ACS, system executive and the crew
		8A	Develop the architecture and interfaces among an autonomous TC subsystem and the station executive, other subsystems and the crew
57-2E	Develop technology for using advanced display and command technology for improving space transportation and platform crew stations	NA	TO BE DEFINED
57-3A	Complete development and testing of advances long-life angular sensor and inertial measuring systems concepts for potential use in spacecraft guidance	NA	TO BE DEFINED
58-1B	Continue development of high-density, wide temperature range magnetic bubble memory devices using ion implant technology	5D	Nonvolatile solid state memory
		5H	Flight quality, high density bulk storage
58-1C	Develop an optical disk recorder capable of ingesting and retrieving data at 50 million bits/second, and storing 10 to the 11th power bits per disk	5H	Flight quality, high density bulk storage
58-1F	Develop a network simulation capability and evaluate network designs for space station	NA	TO BE DEFINED
58-1G	Complete and evaluate ADA in a test environment	NA	TO BE DEFINED
58-1I	Develop very high-speed integrated circuit technology system for use as the general-purpose onboard space station core data processing unit	NA	TO BE DEFINED

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Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
58-1J	Develop high-speed optical data bus network architecture, components, optical nodes, and system consistent with space station data rates/processors	5E	Fiber optics
62-2D	Complete LEO/GEO spacecraft subsystem technology assessment and requirements	NA	TO BE DEFINED
62-2I	Provide spacecraft analytical tool to quantitatively study subsystem interactions	NA	TO BE DEFINED
64-1A	Develop automation assessment methodology and define hierarchical system automation and technology requirements for automated subsystem control/management	NA	TO BE DEFINED
64-1B	Exercise space station models to determine system performance and sensitivity to key configuration parameters and interactions with subsystem	NA	TO BE DEFINED
64-1C	Formulate methodology and techniques to develop a phased system and subsystem simulation/emulation capability	NA	TO BE DEFINED
64-1D	Define requirements for automated systems status monitoring and integrated subsystem techniques for fault detection, isolation, and recovery	2E	Develop implementation methods for monitoring, self-test, malfunction detection and trend analysis
64-1E	Perform system and discipline analysis/trade studies to develop generic requirements for platform systems	NA	TO BE DEFINED
64-1F	Define requirements for artificial intelligence techniques as an enabling technology for system/subsystem autonomous operation	5K	Robotics/Teleoperator/Artificial intelligence/Expert systems

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Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
64-1G	Develop interface concepts, standards, and protocols applicable to advanced space data systems	1B	Develop the architecture and the interfaces of autonomous PROP and the station system executive
		1I	Develop the architecture and the interface for PROP system interactive operations with the space station crew
		7A	Develop an interactive autonomous ACS with and interface to an autonomous NAV
		7B	Develop an interactive autonomous ACS with an interface to an autonomous Traffic Control system
		7E	Develop the architecture of and the interface among an autonomous ACS,system executive and the crew
		8A	Develop the architecture and interfaces among an autonomous TC subsystem and the station executive, other subsystems and the crew
64-1I	Advance the technology needed for automation of the space station power subsystem	NA	TO BE DEFINED
64-1K	Develop and evaluate data management system architecture concepts that would integrate space station facility and user requirements	5I	System executive and data system architectures
		7H	Develop an integrated precision pointing system for small payload control

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Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
64-1L	Define system/subsystem interface architecture requirements to optimize evolutionary growth	NA	TO BE DEFINED
64-1M	Define requirements for crew "safe haven" retreat and transfer to rescue vehicle	NA	TO BE DEFINED
64-1N	Determine space station automation requirements	NA	TO BE DEFINED
64-1O	Develop a system-level functional simulation to examine effects of subsystem performance, interaction, and failure modes, and identify critical	NA	TO BE DEFINED
64-2C	Develop and validate simulation capability to assess man-machine interface and human performance in teleoperated and robotic systems	5K	Robotics/Teleoperator/Artificial intelligence/Expert systems
		7I	Develop the sensing and integrated control technology for the crew and manipulators or teleoperators on board
64-2D	Define space and ground logistics, maintenance, and servicing requirements for platforms, station, and free flying systems in close orbital proximity	NA	TO BE DEFINED
64-2E	Develop simulations for rendezvous and docking maneuvers and define requirements for caution and warning/collision avoidance	NA	TO BE DEFINED
64-2F	Establish allocation of functions to man and machine that optimize overall operational efficiency and utilization of the crew	NA	TO BE DEFINED
NA	No PASO Targets Identified	1A	Develop an autonomous PROP control system to gather, process and store sensor data for system performance and health determination

Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
		1C	Develop an integrated sensing and processing technique for inflight determination of propellant mass and pressurant mass remaining
		1D	Develop an integrated sensing and processing technique for inflight detection, identification location, and isolation of pressurant or propellant leak
		1E	Develop the sensing and processing techniques for autonomous inflight determination of thruster performance and health status
		1F	Develop the sensing and processing techniques for autonomous inflight service and refueling of station and its peripherals
		1G	Develop an autonomous Prop system with interfaces to autonomous NAV and ACS for maneuver planning support and thruster performance assessment
		1H	Develop an autonomous PROP system with ACS interface for thruster inflight calibration
		2A	Develop algorithms and hardware for implementation of configuration control for the complex network of station communication links
		2B	Develop the architecture and the control, feed and operational techniques for an affordable antenna system for the station communication links
		2C	Develop the techniques for the simultaneous operation of the many station communication links in an RFI environment

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Table 3-4. PASO Versus Technology (Cont'd)

PASO	PASO Target Description	No.	Technology Title
		2D	Develop the architecture and techniques to operate the complex and unencumbered intra-vehicular voice nets for the station
		2G	Develop a lightweight, space-qualified radar system for surveillance and traffic control
		5G	Radiation hard microprocessors
		5M	Automated position/time generation
		5N	Hardware design aids
		7C	Flight qualify radiation tolerant computers and memories
		7L	Develop Bite for ACS devices and the interface with autonomous fault protection and maintenance control
		7M	Develop the technology for autonomous adjustment of control laws, and/or adaptive, supervisory fault management system
		8B	Develop an environment sensing pointable radiator system
		8C	Develop onboard trend analysis and thermal performance prediction capability
		9A	Develop an autonomous navigation system for establishing the station orbit and maintaining the orbit
		9B	Develop a crew - interactive navigation system to monitor and control the orbit of free-flying vehicles which interact with the space station.

APPENDIX A

AUTONOMY TECHNOLOGY NEEDS FOR SUBSYSTEM DISCIPLINES

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CONTENTS

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INTRODUCTION AND USAGE GUIDE

This appendix contains descriptions and ranking of technologies to support the functions that are candidates for automation as well as the functions that would benefit from technology development.

The approach to establishing technology needs to support a space station effort consisted of the following steps.

1. Define space station functions.
2. Assess the need for each function to be automated.
3. Assess the availability of technology to automate the function.
4. Identify areas where technology development is needed to automate the function.
5. Prioritize the technology development needs.

Following the above process, the data contained in this appendix were generated by a team of spacecraft engineers representing discipline areas associated primarily with unmanned spacecraft. It is believed the data are generally applicable to manned space vehicle, but because of additional functions required to sustain the man as part of the manned system, the data are not complete.

The package is organized by discipline area in the following order:

Discipline Code	Discipline Name
1	Propulsion (PROP)
2	Communications and Tracking (C&T)
4	Electrical Power (EPS)
5	Data Management System (DMS)
7	Guidance and Control (G&C)
8	Temperature Control (TC)
9	Navigation (NAV)

In each discipline area, the data is presented in the following order:

- List of technologies related to that discipline.
- A priority ranking of technologies.
- A data sheet for each technology.
- The list of functions that are candidates for automation.
- The list of functions that would benefit from technology development.

To provide correlation between different sections, a code number was assigned to each technology topic and a function number was assigned to each function. The only significance to the technology code is that the numeric identifies the discipline area as shown above. The significance of the function number is that the digits to the left of the decimal identify a major function and the digits to the right of the decimal identify in the following order: Discipline area, Level 1 function, Level 2 function .... Level N function.

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PROPULSION SYSTEM TECHNOLOGIES

Code	Title
1A	Develop an autonomous PROP control system to gather, process and store sensor data for system performance and health determination.
1B	Develop the architecture and the interfaces of autonomous PROP and the Space Station system executive.
1C	Develop an integrated sensing and processing technique for inflight determination of propellant mass and pressurant mass remaining.
1D	Develop an integrated sensing and processing technique for inflight detection, identification location, and isolation of pressurant or propellant leakage.
1E	Develop the sensing and processing techniques for autonomous inflight determination of thruster performance and health status.
1F	Develop the sensing and processing techniques for autonomous inflight servicing/refueling of the space station and its peripherals.
1G	Develop an autonomous PROP system with interfaces to autonomous NAV and ACS for maneuver planning support and thruster performance assessment.
1H	Develop an autonomous PROP system with ACS interface for thruster inflight calibration.
1I	Develop the architecture and the interface for PROP system interactive operations with the space station crew.

PROPULSION SYSTEM TECHNOLOGIES

PROP TECHNOLOGY PRIORITY RANKING

Code	Title	Category	Ranking
1A	Autonomous PROP Control System	A	1
1B	Architecture and Interfaces	A	2
1C	Propellant and Pressurant Mass Determination	A/B	3
1F	Sensing and Processing for Inflight Servicing and Refueling	A/B	4
1D	Sensing and Processing of Pressurant or Propellant Leakage	B	5
1E	Sensing and Processing for thruster performance and Health Checks	B	6
1G	Maneuver Planning Interfaces with NAV & G&C	AD	7
1H	Thruster Inflight Calibration Interface with G&C	B	8
1I	Architecture and Interface with Crew	AD	9

Category Legend:

A - Technology development needed for any capability.

B - Technology development needed for extensive capability

C - Technology development desirable but not critical.

D - Technology development applicable to far-term application only.

E - Technology development need is undefined.

AD - Advanced development not technology development.

NA - Not applicable for PROP technology development.

PROPULSION SYSTEM TECHNOLOGIES

1A Develop an autonomous PROP control system to gather, process and store sensor data for system performance and health determination.

Description

Process and store sensor data for:

a) Thruster performance evaluation
b) System component health status
c) Consumables management
d) Audit trail

Justification

Development of this propulsion control system is the basis for an autonomous PROP system. Provides basic redundancy control function.

Issues

a) Level of redundancy/switching capability
b) Number and types of sensors

Precedents

ASP: ARMMS development

Technology Readiness

Today: Research and Development (Level 2)

PROPULSION SYSTEM TECHNOLOGIES

1B Develop the architecture and the interfaces of autonomous PROP and the SS system executive.

Description

Develop the architecture and interfaces which provide data and command support for system-wide distribution of data to and from PROP including crew interface data:

1) Propellant feed system and thruster configuration.
2) Propellant tank, feed system (valve) and thruster health status.
3) Thruster pefrmance parameters.
4) Thruster/valve life cycle status.
5) Fault protection; alarm and alert indications.
6) Initiation/override of routine maintenance.

Justification

Development of this PROP architecture and interfaces form the basis for an autonomous PROP. This architecture is the basis for continuing the transfer of PROP function support from the ground/crew to machine.

Issues

1) Architecture selection; partitioning of duties.
2) Interface protection.

Precedents

1) Galileo
2) ARMMS

Technology Readiness

Today: Research and Development (Level 2/3)

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1C Develop an integrated sensing and processing technique for inflight determination of propellant mass and pressurant mass remaining.

Description

Accepts inputs from a direct mass sensor on each tank and processes the data to compute mass remaining in each tank. Mass transfer rate determination for fuel transfer/servicing control.

Justification

Reliable and accurate real time determination of propellant and pressurant mass remaining and its position will be required to support consumables management including servicing/refueling operations and mass properties determination for an evolving station.

Issues

1) Degree of implementation on the initial station.
2) Selection of the sensing devices. and integration with the flight tankage.

Precedents

- NASA OAST-funded studies
- USAF-funded studies

Technology Readiness

Today: Basic Research and Development (Level 2)

PROPULSION SYSTEM TECHNOLOGIES

1D Develop an integrated sensing and processing technique for inflight detection, identification, location, and isolation of pressurant and propellant leakage.

Description

Accepts inputs from a series of sensors and processes the data to detect, identify and locate propellant or pressurant leakage.

Justification

Reliable and accurate real time detection and location of propellant or pressurant leakage will be required to support consumables management, space station contamination control and crew safety. Fault protection is provided.

Issues

1) Degree of implementation on the initial station.
2) Selection of the sensing devices and integration with the flight pressurant and propellant feed/transfer system.

Precedents

1) NASA/OAST-funded studies.
2) USAF-funded studies.

Technology Readiness

Today: Basic Research and Development (Level 2).

PROPULSION SYSTEM TECHNOLOGIES

1E Develop the sensing and processing techniques for autonomous inflight determination of thruster performance and health status.

Description

Accepts inputs from a variety of sensing sources and processes data to compute:

a) Thruster valve performance/health.
b) Thruster performance/health.
   1) Pulse performance (ACS contributes).
   2) Steady state performance (NAV contributes).
   3) Embedded temperature and flow sensors.

Justification

Inflight thruster performance and health assessment support real time control of space station propulsive maneuvers and provides performance trend analysis for the evolving station.

This function removes performance assessment dependence on prelaunch knowledge and provides fault protection.

Issues

Degree of implementation on the initial station.

Precedents

1) STS ACS thruster leak detector.
2) NASA/OAST-funded studies.

Technology Readiness

Today: Basic Research and Development (Level 2-3)

PROPULSION SYSTEM TECHNOLOGIES

1F Develop the sensing and processng techniques for autonomous inflight servicing/refueling of the space station from an orbiting tanker and space station servicing/refueling of free flyers or experiment modules attached to the station.

Description

1) Develop an autonomous servicing/refueling probe with command and data interfaces for tanker-to-space station and space station-to-free flyer for:

   a) Sensor data acquistion
   b) Executive command transfer
   c) Executive system data exchange
   d) Probe leakage sensing and correction

2) Develop an integrated mass and mass rate sensing, processing and control technique for propellant and pressurant transfer.

   a) Tanker to space station
   b) Space station to free flyer

Justification

Inflight servicing/refueling of the space station from an orbiting tanker module will be required to support continuing operation as the station evolves. Servicing/refueling of experiment modules and free flyers will be required for long-term operations.

Issues

1) Degree of implementation on the initial station.
2) Development of the sensing devices and servicing probe.

Precedents

1) NASA/OAST-funded studies.
2) USAF-funded studies.

Technology Readiness

Today: Basic Research and Development (Level 2).

PROPULSION SYSTEM TECHNOLOGIES

1G Develop an autonomous propulsion system with interfaces to autonomous NAV and ACS for maneuver planning support and thruster performance assessment.

Description

Interface includes data support for:

PROP -> NAV	1) Propulsive capability remaining 2) Consumables remaining 3) Predicted thruster on time for required delta V
NAV -> PROP	Required delta V and direction.
PROP -> ACS	1) Thruster health status 2) Thruster life cycle status 3) Thruster performance
ACS -> PROP	Thruster health status input from ACS

Justification

Development of a propulsion system with NAV and ACS interfaces supports autonomous orbit maintenance with real time performance constraints. Crew/ground control through the system executive.

Issues

1) Extent of real time maneuver control exercised by the system executive.

2) Design of ground, system executive and crew management/control of these interfaces.

Precedents

ASP: ARMMS development.

Technology Readiness

Today: Research and Development (Level 2).

PROPULSION SYSTEM TECHNOLOGIES

1H Develop an autonomous propulsion system with ACS interface for thruster inflight calibrations.

Description

Perform thruster calibration from ACS momentum unload to assess:

1) Inflight performance determination.
2) Long-term inflight changes.

Justification

Determines thruster/system performance in actual/current operational environment. Factors in space station configuration changes/growth.

Issues

1) Thruster control function used.
2) Performance accuracy requirements.

Precedents

ASP: ARMMS development

Technology Readiness

Today: Research and Development (Level 2).

PROPULSION SYSTEM TECHNOLOGIES

11 Develop the architecture and the interfaces for PROP system interface operations with space station crew.

Description

Develop the architecture and interfaces which provide data and command support for executive/crew control of:

1) Fault recovery and routine maintenance
2) Consumables assessment
3) Maneuver design/execution
4) Configuration changes
5) Algorithm programming and parameter changes
6) Propellant transfer/refueling

Justification

Development of this architecture supports interactive operation between the propulsion system and the crew.

Issues

1) Architecture selection, partitioning of duties
2) Executive control priority requirements

Precedents

1) Galileo
2) ARMMS

Technology Readiness

Today: Research and Development (Level 2)

JPL D-1197

ASST SPACE STATION FUNCTIONS-PROPULSION

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
2.11000000	Provide thruster configuration/selection	1a 1b
4.10000000	Receive, store, generate, and distribute commands-PROP	1b
7.12000000	Monitor PROP subsystem for leakage	1d 1f 1h
8.11000000	Provide propellant mass remaining for propulsive maneuvers	1a 1b
8.12000000	Provide propulsive capability remaining (delta V)	1a 1b
8.13000000	Provide thruster on time estimate for propulsive maneuvers	1a 1b
10.11000000	Provide PROP telemetry conversion to engineering units	1b
10.12000000	Provide PROP audit trail data for autonomous operation periods	1a 1b
13.11100000	Determine mass of propellant used for maneuvers	1c 1a
13.11200000	Determine propellant leakage	1d
3.11300000	Determine propellant mass transfered for refueling	1f
13.12100000	Determine pressurant leakage	1d
13.12200000	Determine pressurant mass transfered for refueling	1f
14.11100000	Provide PROP configuration status table	1a 1b
14.11120000	Component health status	1a
14.11200000	Thruster configuration management	1a
14.12400000	Thruster performance assessment	1a 1h 1i
15.11000000	Thruster status table	1a
15.12000000	Propellant mass and cg estimation	1a 1i
15.13000000	Translation maneuver duration estimates	1b 1g
15.14000000	Thruster calibrations (momentum wheel unload)	1a 1h
15.15000000	Thruster performance analysis	1a gh i
15.16000000	Thruster life management	1a gh i

JPL D-1197

ASST SPACE STATION FUNCTIONS-PROPULSION

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CODE
2.11000000	Provide thruster configuration/selection	1a 1b
4.10000000	Receive, store, generate, and distribute commands-PROP	1b
7.12000000	Monitor PROP subsystem for leakage	1d 1f 1h
8.11000000	Provide propellant mass remaining for propulsive maneuvers	1a 1b
8.12000000	Provide propulsive capability remaining (delta V)	1a 1b
8.13000000	Provide thruster on time estimate for propulsive maneuvers	1a 1b
10.11000000	Provide PROP telemetry conversion to engineering units	1b
10.12000000	Provide PROP audit trail data for autonomous operation periods	1a 1b
13.11100000	Determine mass of propellant used for maneuvers	1c 1a
13.11110000	Sensor - Direct mass measurement	1c
13.11200000	Determine propellant leakage	1d
13.11300000	Determine propellant mass transfered for refueling	1f
13.12100000	Determine pressurant leakage	1d
13.12200000	Determine pressurant mass transfered for refueling	1f
14.11100000	Provide PROP configuration status table	1a 1b
14.11120000	Component health status	1a
14.11121100	Positive position indicator	1a
14.11200000	Thruster configuration management	1a
14.12400000	Thruster performance assessment	1a 1h 1i
14.12421000	Sensors- Temperature, pressure, flow	1f 1c 1d
15.11000000	Thruster status table	1a
15.12000000	Propellant mass and cg estimation	1a 1i
15.13000000	Translation maneuver duration estimates	1b 1g
15.14000000	Thruster calibrations (momentum wheel unload)	1a 1h

ASST SPACE STATION FUNCTIONS-PROPULSION

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CO DE
15.15000000	Thruster performance analysis	1a gh i
15.16000000	Thruster life management	1a gh i

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COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-A. Develop algorithms and hardware for implementation of configuration control for the complex network of Space Station communication links.

2-B. Develop the architecture and the control, feed and operational techniques for an affordable antenna system for the Space Station communication links.

2-C. Develop the necessary techniques (i.e., identification, compensation, etc.) for simultaneous operation of the many Space Station communication links in an RFI environment (including SS generated RFI).

2-D. Develop the architecture and necessary techniques to operate the complex and unencumbered intra-vehicular voice nets for the Space Station.

2-E. Develop implementation methods for monitoring, self-test, malfunction detection and trend analysis.

2-F. Develop an RF and/or optical docking and rendezvous sensor system.

2-G. Develop a lightweight, space-qualified radar system for surveillance and traffic control.

COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

Code	Title	Category	Ranking
2-C	Simultaneous Operation of Communication Links	A	1
2-F	Docking and Rendezvous Sensor System	A	2
2-B	Affordable Antenna System	A	3
2-G	Surveillance and Traffic Control Radar	A	4
2-A	Configuration Control of Communication Links	B	5
2-D	Intravehicular Voice Net Operation	B	6
2-E	Monitoring, Self-test and Malfunction Detection	C	7

Category Legend:

- A - Technology development needed for any capability.
- B - Technology development needed for extensive capability
- C - Technology development desirable but not critical.
- D - Technology development applicable to far-term application only.
- E - Technology development need is undefined.
- AD - Advanced development not technology development.
- NA - Not applicable for C&T technology development.

2-A. Develop algorithms and hardware for implementation of configuration control for the complex network of Space Station communication links.

Description:
Automatically control the configuration of communication and metric tracking links to:

a) the ground via TDRSS
b) Global Positioning System (GPS) satellites
c) docking and rendezvousing spacecraft
d) All other Space Station constellation vehciles
e) EVA units.

Parameter control includes:

a) power level vs. range to Earth, EVA, etc.
b) frequency selection
c) coding/encryption selection
d) receiver sensitivity selection
e) data rate, mod index and mod techniques selection
f) antenna selection
g) voice and video link configurations
h) redundancy selection.

Rationale/Justification:
The Space Station will have many RF communication links operating simultaneously (to ground, other spacecraft, EVA, IVA, etc.). Each will have parameters that must be switched or adjusted as a function of time. Not all will be predictable for sequence generation as in the Voyager (and other) spacecraft. Some will be related to spacecraft trajectories and realtime operations. Shuttle operations requires manual control for most of these configuration changes. Space Station operations will be too complex for manual control and will require autonomous control for communication link configuration.

Issues:

a) Power level selection to provide the necessary capability but not exceed RFI and safe impingment (ground, EVA, etc.) flux density levels.
b) Coding and encryption necessary to provide performance and security requirements.
c) Simultaneous link requirement.
d) Interaction and compatibility between multiple links.
e) Interface with data system.
f) Wideband matrix switch development.
g) Routing algorythm.
h) Complexity of network.

Precedents:
a) Task force, Space Station Information System.
b) Air Force ASP.
c) Computer-controlled sequences for spacecraft configuration.
d) DSS-13 remote-controlled station.

Technology Readiness: a) Today: Level 1

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COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-B. Develop the architecture and the control, feed and operational techniques for an affordable antenna system for the Space Station communication and metric tracking links.

Description:

Provide spherical antenna coveage for a communication system having multiple links operating at different power levels, different frequencies with different pointing requirements and various viewing obstacles.

Rationale/Justification:

The Space Station will require spherical coverage for RF visibility of many simultaneous communication links. It must track each source, some with high-gain capability, with independence from Space-Station attitude control constraints. Affordable, phased-array beam-steering techniques must be developed for autonomous operation of many simultaneous communication links.

Issues:

a) Affordable, phased-array beam-steering techniques.
b) Multiple frequencies with a common tracking locus.
c) Multiple links with different and varying tracking loci.
d) Spherical coverage with viewing obstacles.
e) RF polarization tracking.
f) Independence from Attitude Control Constraints.
g) Acceptable mechanical reactions to steering forces imparted to the space station.
h) Complexity of network.

Precedents: a) NASA OAST funded studies.

Technology Readiness: a) Today: Level 2-3

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COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-C. Develop the necessary techniques (i.e. identification, compensation, etc.,) for simultaneous operation of the many Space Station communication links in an RFI environment (including Space Station generated RFI).

Description:

Each communication link must operate with acceptable performance in an environment with RF energy from many sources. Some sources are "citizen" and can be predicted but may cause adverse effects. Other sources are "alien" and to a certain extent, unpredictable.

Rationale/Justification:

With numerous two-way communication links centered at the Space Station, there will be many RF energy sources in the Space Station vicinity. In addition, other sources (i.e., spacecraft-to-ground/TDRS links, satellite links, ground-based near-earth and deep-space radar, jamming, etc.) will pass through the vicinity at various (and some unpredictable) times. Autonomous operation must provide for successful Space Station communications in this environment.

Issues:

a) Understand and control or compensate for all "citizen" generated RFI.
b) Detect, monitor, characterize and compensate for all "alien" generated RFI.
c) Develop anti-jam and spoofing protection techniques.
d) Spectrum analyzer hardware.
e) Sensor hardware.
f) Identification algorithms.
g) Response algorithm.
h) Complexity of network.

Precedents:
a) Search for Extra-Terrestrial Intelligence (SETI)
b) DSN RFI Surveilance.
c) Electromagnetic Compatibility Analysis Center
d) TDRSS RFI Analysis.

Technology Readiness: a) Today: Level 1-2

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COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-D. Develop the architecture and necessary techniques to operate the complex and unencumbered intravehicular voice nets for the Space Station.

Description:

Intravehiclar Activity (IVA) will require a complex network of umbilical-free voice links in an environment with possible RFI, audio background noise and reasonant chambers. It will require voice recognition for an audio commanding capability and voice synthesis for configuration and status reporting and caution and warning.

Rationale/Justification:

IVA will require a complex communication network with many potential design problems (i.e., resonant chambers, private communications, conference nets, background noise, voice recognition, voice synthesis wireless units, etc.). Although technologies exist to provide each capability, the complex network and system configuration for autonomous operation will require some study and development.

Issues:

a) Voice recognition and voice synthesis.
b) Background noise suppression and elimination of undesirable acoustic coupling between nets.
c) Power consumption of portable, wireless voice communication units.
d) Integration with extravehicular activities (EVA).
e) Complexity of network.

Precedents:
a) Existing IBM & JSC developmental IR-Scatter Systems.
b) TI voice modules (synthesis and recognition).
c) BTL Voice Recognition.

Technology Readiness: a) Today: Level 2-5

COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-E. Develop implementation methods for monitoring, self-test, malfunction detection and trend analysis.

Description: An autonomous capability must be implemented to provide subsystem performance and health monitoring as well as malfunction detection and correction. The present capability must be further developed and augmented to include activities performed by ground analysts such as:

a) periodic tests,
b) trend analysis,
c) gradual degradation detection leading to redundant component switching prior to a "failure."

Rationale/Justification:

These activities which are presently performed primarily with manual control, data reduction, decision making, response generation, etc., are very time-consuming and thus quite costly. The technology exists to provide the capability for autonomous performance. However, a considerable amount of study and advanced development is needed to implement this autonomous operation.

Issues:

a) Development and implementation of an automated (computer-controlled) function to monitor, test and configure the subsystem.
b) Range and angle accuracy of metric tracking.
c) Comparison of actual vs predicted signal levels.
d) Frequency response curves (and comparisons).
e) Bit-error rate verification.
f) Spectrum analysis.
g) Acquisition times.

Precedents:
a) JPL Telecommunications Performance and Analysis System (TPAS).
b) DSS-13 Remote Controlled Station.

Technology Readiness:
a) Today: Level 2-4

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COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-F. Develop an RF and/or optical docking and rendezvous sensors system.

Description: A sensor system must be developed using Rf or optical techniques (or a combination) that will monitor and display the position and orientation of a docking vehicle (relative to the Space Station) as it approaches and docks.

Rationale/Justification:

Docking a vehicle (Shuttle Orbiter, spacecraft, etc.,) to the Space Station will require a position, velocity and attitude determination system with sub-millimeter accuracy. The technology needs further development to provide the capability required for the Space Station.

Issues:

a) Development of a sensor system that will determine and display position, orientation, range, acceleration, attitude and rate of attitude change with accuracies to less than a millimeter.

Precedents:
a) JSC - H. Irwin, bicycle reflector 1% of range accuracy laser ranging.
b) JPL - C. Berdahl, laser ranging system.
c) JPL - J. McLauchlan, et al, Spacial High-Accuracy Position-Encoding Sensor, for Space System Control Application (SHAPES).

Technology Readiness: a) Today: Level 2-3

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COMMUNICATIONS AND TRACKING SYSTEM TECHNOLOGIES

2-G. Develop a light-weight, space-qualified radar system for surveillance and traffic control.

Description:

A compact, light-weight radar system must be developed that will provide the necessary surveillance for space traffic control. It must track and verify trajectories of all known spacecraft in the space station vicinity. It must also detect, locate and generate ephemerides for all unknown objects (alien vehicles and space debris) in and approaching the space station vicinity.

Rationale/Justification:

Space Station surveillance requires detection, recognition, tracking and ephemeris generation of all objects (including "alien" spacecraft and space debris) within a sphere of 2000 Km radius, centered at the Space Station. Although surveillance is performed (to a degree) with ground based radar, a significant amount of technology development is required to develop a compact, space-qualified surveillance system.

Issues:

a) Development of a light-weight space-qualified system.
b) Ephemeris generation of alien spacecraft and space debris.

Precedents:

a) FAA ground-based air traffic control radar.

Technology Readiness: a) Today: 2-4

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ASST SPACE STATION FUNCTIONS-COMMUNICATIONS AND TRACKING

Area code 1=PROP 2=C&T 3=DPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
6.21300000	Provide RFI immunity	2c
6.21400000	Provide independence from attitude control constraints.	2b
6.23200000	Voice links, some simultaneous/conferences	2a
6.23300000	Video links	2a
6.23720000	Surveilance radar, alien vehicle and space debris	2g
6.23800000	Docking and rendezvous sensor system	2f
6.24100000	Voice nets	2a
6.25000000	Provide automatic configuration management	2a
6.26300000	Provide "built-in-test" capability for malfunction detection and reporting.	2e
6.26410000	Provide subsystem trend analysis and malfunction determination	2e
4.23000000	Provide emergency command capability.	2b
17.21100000	Voice nets [6.24100000]	2d
18.22000000	Perform periodic test and calibration	2e
19.21000000	Provide antenna pointing and control	2b

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ASST SPACE STATION FUNCTIONS-COMMUNICATIONS AND TRACKING

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6.23800000	Docking and rendezvous sensor system	2f
6.24100000	Voice nets	2a
6.25000000	Provide automatic configuration management	2a
6.26300000	Provide "built-in-test" capability for malfunction detection and reporting.	2e
6.26410000	Provide subsystem trend analysis and malfunction determination	2e
4.23000000	Provide emergency command capability.	2b
17.21100000	Voice nets [6.24100000]	2d
18.22000000	Perform periodic test and calibration	2e
19.21000000	Provide antenna pointing and control	2b

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POWER SYSTEM TECHNOLOGIES

4A State of Charge Indicator/Adaptive Charging

4B Compact, Nonintrusive, Low Mass Voltage, Current, and Switch Position Sensors

4C High Voltage, High Power DC Switches and Circuit Breakers

POWER SYSTEM TECHNOLOGIES
POWER AUTONOMY TECHNOLOGY PRIORITY RANKING

Code	Title	Category	Ranking
4-A	State of Charge Indicator	A* E	1
4-B	Voltage, Current, and Switch Position Sensors	B	2
4-C	High Voltage-High Power DC Switches and Circuit Breaker	A** AD	3

*A category if battery parameters not monitored frequently.

**A category if a DC distribution system is selected.

Category Legend:

A - Technology development needed for any capability.

B - Technology development needed for extensive capability

C - Technology development desirable but not critical.

D - Technology development applicable to far-term application only.

E - Technology development need is undefined.

AD - Advanced development not technology development.

NA - Not applicable for EPS technology development.

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POWER SYSTEM TECHNOLOGIES

4A Technology

State of Charge Indicator/Adaptive Charging

Justification

Existing power systems routinely provide for battery charging/discharging during each orbit. Such conventional systems, however, cannot detect or compensate for small current drains or small changes in battery parameters which can leave the batteries totally depleted after several days or weeks of routine charging. An automated power system subject to long periods of unattended operation must be capable of detecting such gradual changes and of taking the required compensating action (such as adaptive charging) to guarantee a full state of charge prior to each occultation. Existing state of charge indicators are not sufficiently accurate for the required durations and do not have adaptive charging capabilities. Such capabilities are required for the initial Space Station to reduce crew/ground monitoring costs.

Issues

Accuracy of state of charge indicator
Degree of adaptiveness
Control/algorithm procedures

Precedents

Terrestrial/Electric Vehicle Programs

Technology Readiness

Level 4-5

POWER SYSTEM TECHNOLOGIES

4B Technology

Compact, Nonintrusive, Low Mass Voltage, Current, and Switch Position Sensors

Justification

Automated power system functions such as load management, fault detection and isolation, energy storage charge/discharge cycling, and routine periodic health/calibration self-testing all require a large number of sensor units to function properly. Existing electrical sensors embedded within the power distribution network can impact power system efficiency and stability when used in large quantities to completely monitor a large Space Station. Existing sensors are also comparatively massive and occupy significant volume. An ideal sensor would be a nonintrusive, high-efficiency, low-mass low-volume device. A fiber optic power sensing network shows potential for approaching this ideal sensing state. Fiber optic current, voltage, and switch position sensors have been concept-demonstrated but significant effort is still required before fiber optic sensors can replace conventional electrical sensors. Given adequate funding, it appears that fiber optic power sensors can provide a significant enhancement of power system automation for the initial Space Station.

Issues

Accuracy/availability/cost

Precedents

Industrial fiber optic communications

Technology Readiness

Level 4

POWER SYSTEM TECHNOLOGIES

4C Technology

High Voltage, High Power DC Switches and Circuit Breakers

Justification

Existing work on high voltage, high power DC switches and circuit breakers may required additional microprocessor interfaces to support an automated initial Space Station.

Issues

Capability/Requirements/Funding

Precedents

Existing OAST-funded programs.

Technology Readiness

Level 4-5

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ASST SPACE STATION FUNCTIONS-POWER

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV
Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
1.41110000	Control solar array output	
1.41120000	Control Solar Array Attitude (ACS)	
1.41211000	Provide battery charge control	
1.41212000	Provide battery discharge control	
1.42100000	Acquire margin measurement data	
1.42200000	Calculate present power margin	
1.42300000	Predict future power margin	
1.42310000	Calculate load demand for next commanded state	
1.42320000	Verify next commanded load state will maintain a positive power margin	
1.43000000	Regulate Power Bus Voltage	
1.44000000	Direct and Control Power Distribution	
1.46000000	Provide Required uninterrupted power supply (UPS) Electrical Energy	
2.42100000	Maintain power service during eclipse	
2.42200000	Maintain power service to essential loads during off sun maneuvers (for solar array power sources)	
4.42000000	Provide capability for data transfer of power related commands	
4.43000000	Provide data storage for the EPS	
4.44000000	Provide data processing for the EPS	
5.42000000	Transfer data and/or requests for environmental control for EPS	
8.42000000	Provide power profile data and estimates for sequences	4b
9.42000000	Provide means to receive external timing/synch signals for power subassemblies	
10.42000000	Provide power status	
10.43000000	Provide power engineering data	
.41000000	Provide assessment of power state	
13.42000000	Provide assessment of battery state	4a

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ASST SPACE STATION FUNCTIONS-POWER

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
13.43100000	Sense power sources	
13.43200000	Sense batteries	
13.43300000	Sense distribution and control	4b
13.43400000	Sense secondary conversion units	
13.44100000	Control solar array operating point	
13.46000000	Execute power distribution commands	
14.41000000	Detect, Isolate and Recover from Power Subsystem Faults	
14.41200000	Inform executive control subsystem of battery failure	
14.41300000	Isolate battery from power bus and inform executive of action	
14.41400000	Condition battery and connect same to the power bus	
14.41500000	Executive informs EPS that battery has been replaced	
14.42000000	Detect and Isolate User Subsystem Power Faults	4b
14.43000000	Perform Fault Verification Prior to Initiating a Response	4b
14.44000000	Perform Periodic Health Checks of the Power Subsustem Computer Function	
15.41000000	Provide battery reconditioning	
15.41100000	Sense Degraded Battery Performance	4a
15.41200000	Verify that Predicted Power Margins will allow a battery to be reconditioned	
15.41300000	Initiate battery reconditioning	
18.41000000	Provide test/calibration capability at the subsystem level	4b
18.42000000	Provide test/verification capability at the subassembly level	4b
18.43000000	Provide test/fault isolation capability at the replacement unit/component level	4b 4c
20.42000000	Provide audit trail during power faults/overloads	

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ASST SPACE STATION FUNCTIONS-POWER

Area code 1=PROP 2=C&T 3=DPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV
Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CODE
8.42000000	Provide power profile data and estimates for sequences	4b
13.42000000	Provide assessment of battery state	4a
13.43300000	Sense distribution and control	4b
14.42000000	Detect and Isolate User Subsystem Power Faults	4b
14.43000000	Perform Fault Verification Prior to Initiating a Response	4b
15.41100000	Sense Degraded Battery Performance	4a
18.41000000	Provide test/calibration capability at the subsystem level	4b
18.42000000	Provide test/verification capability at the subassembly level	4b
18.43000000	Provide test/fault isolation capability at the replacement unit/component level	4b 4c

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DATA MANAGEMENT SYSTEM TECHNOLOGIES

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5.A Software Development Aids.

5.B Man/Machine Interfaces.

5.C Custom VLSI Manufacturing/Testing.

5.D Non-volatile Solid State Memory.

5.E Fiber Optics.

5.F Fault Tolerant Microcomputers.

5.G Radiation Hard Microprocessors.

5.H Flight Quality, High Density Bulk Storage.

5.I System Executive and Data System Architectures.

5.J Special Purpose Algorithm Development.

5.K Robotics/Teleoperators/Artificial Intelligence/Expert Systems.

5.L Automated Sequence/Command Generation.

5.M Automated Position/Time Generation.

5.N Hardware Design Aids.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Code	Title	Category	Ranking
5F	Fault Tolerant Microcomputers	A	1
5C	Custom VLSI Manufacturing/Testing	B	2
5D	Nonvolatile Solid State Memory	C	3
5H	Flight Quality, High Density Bulk Storage	C	4
5E	Fiber Optics	D	5
5K	Robotics/Teleoperators/Artifical Intelligence/Expert	D	6
5G	Radiation Hard Microprocessors	E	7
5A	Software Development Aids	AD	
5B	Man/Machine Interfaces	AD	
5I	System Executive and Data System Architectures	AD	
5J	Special Purpose Algorithm Development	AD	
5L	Automated Sequence/Command Generation	AD	
5M	Automated Position/Time Generation	NA	
5N	Hardware Design Aids	AD	

Category Legend:

A - Technology development needed for any capability.

B - Technology development needed for extensive capability

C - Technology development desirable but not critical.

D - Technology development applicable to far-term application only.

E - Technology development need is undefined.

AD - Advanced development not technology development.

NA - Not applicable for DMS technology development.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title: 5.A Software Development Aids

Description: There is always a need for better software aids and tools. Includes things like:
- More sophisticated/efficient High Order Languages.
- Improved software development systems.
- Special purpose macro-compilers.

Rationale: Since software is the major cost driver in most systems today, and the state-of-the-art for software development aids is far from the theoretical limit, this should be a continuing effort within NASA.

Issues: Private industry pursues this area of technology with vigor and it could be argued that NASA need not be involved, but maintaining expertise is extremely important.

Precedents: With the microprocessor revolution (microprocessors everywhere) software development aids were needed and were developed. Additional capability in this area can only be beneficial to those responsible for software development.

Technology Readiness: Since we are talking about improvements to an existing capability, the technology readiness for the current capability is all ready at a 7. On a theoretical scale of what is ultimately possible, it could be considered to be about a 4-5 now.

Schedule: This activity could be viewed as a level-of-effort activity, but significant progress could be expected every few years.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title: 5.B Man/Machine Interfaces

Description: This includes methods for more efficient transfer of man's thoughts into machine actions. It would include things like software development aids, more capable terminals, better display devices, or even voice communicaions with machines.

Rationale: Any time machines are being used to replace humans, as in automation of certain Space Station functions, the requirement comes up to transfer human thoughts into language that is compatible with the machine. Since this process (developing software) consumes such a large portion of the availale resources for a given system, anything that will make the process more efficient is of extreme value.

Issues: It could be argued that private industry is pursuing this area of technology adequately, and that NASA need not be involved. It is felt that NASA should be involved in establishing requirements, setting goals, and even funding portions of the technology development in order to maintain expertise and insight as to future capabilities.

Precedents: As previously stated, most of the development of this technology has been with private industry. They have recognized the need for making machines more simple to use in order to sell more of their commercial hardware items. The development of microprocessors and the personal computer have driven the need for this technology.

Technology Readiness: As with the software development aids, we are dealing with a technology that is completely developed for a particular level of capability, and as such is all ready at a level 7. On a theoretical scale of what is ultimately possible, it is probably about a level 4-5 now and pursuing the technology to improve it's capability would be the goal.

Schedule: This activity could be viewed as a level-of-effort activity, but significant progress could be expected every few years.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title	5.C Custom VLSI Manufacturing/testing
Description	Very large scale integrated circuitry for microprocessors, memories, and logic arrays particularly suited to data management systems.
Rationale	The multiplicity of processors in the data system, particularly if they are to be fault tolerant, requires that each be of minimal size. The use of VLSI substantially reduces interconnections between circuit packages as well as the obvious volume/weight reductions.
Issues	This development area is being worked on almost everywhere, including JPL. The activity should be vigorously pursued in both support and monitoring to insure that the automated space station applications are addressed.
Precedents	The entire integrated circuitry development activity has been directed toward the conservation of silicon real estate by putting more on each chip
Technology Readiness	Regular arrays for ROMs, PLAs, and RAMs in the order of half a million gates per chip are currently being worked on in the commercial sector. Higher reliability devices with less density are also state of the art in development labs, Level 4.
Schedule	In less than 2 years commercial developments should be qualified for use, but special purpose VLSI for this particular application will not be at level 7 for 4 years.

Title	5.D Non-Volatile Solid State Memory
Description	Static computer memories which maintain alterable contents when power is removed and reapplied.
Rationale	Most solid state memory devices used with microcomputers are volatile and the small computer systems rely on bulk magnetic storage to record data and programs during periods of inactivity. The manual intervention needed for reloading is not a viable option in an autonomous space station.
Issues	There is not a great deal of emphasis in the commercial sector for this product as it is more suited to critical or unattended control systems. Some effort is being devoted though to combining electrical eraseable PROMs and static RAMs on the same chip to acheive the function.
Precedents	These devices are again a natural product of the integrated circuit development being the analog of the magnetic core memory.
Technology Readiness	Non-volatile RAM of 4k bits per chip are now available, but they are relatively slow and require voltages not normally used in microprocessor systems. Level 4-5.
Schedule	Lower voltage units of the same density and somewhat faster are predicted for the end of this year. This would indicate that qualified units of the density needed might not be available until 1987.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title	5.E Fiber-Optics
Description	Glass fiber communication links for distributed data system buses and analog voice and instrument information transfer.
Rationale	The glass fiber as a data transfer medium is characteristed by very wide bandwidth, light weight, free of the effects of EMI and EMP, non-radiative, and relatively radiation proof. Would replace conductive buses in the data management system and could be used in support of EVA.
Issues	Fiber-optics for long haul communication require high power light sources and very sensitive fast detectors for the transmit and receive functions. This is not the case for local area networks. The cost per termination is still high for commercial application, especially if integrated optics are used, but the advantages would offset this aspect in space station use.
Precedents	Glass fiber technology is currently being pursued by communication companies for the bandwidth and copper saving aspects and by the military for the security and electromagnetic immunity aspects. Connections, heterogeneous lasers, avalanche diodes, and the drawing and cladding of fibers are all receiving much attention.
Technology Readiness	At present, off the shelf data links are available with bandwidths of tens of megahertz and analog capability well into the vhf. These have not been characterized as to immunity to low level radiation over long period, but this is the subject of experiments now being planned, Level 4.
Schedule	Qualified short haul links for ground use are now available, but space ready hardware will probably not be available for 3 to 4 years.

Title	5.F Fault Tolerant Microcomputers
Description	Microcomputers for data management systems employing self-checking and replacement and/or voting means to avoid faults in computation or data processing in applications needing high reliability.
Rationale	Almost all application of a computer on a space station are critcal and demand the highest reliability commensurate with repairability. This is obviously particularly true during the unattended periods.
Issues	Fault tolerance gain be acheived in many different ways but current thinking has extended beyond the hardware reliability into the software. In an application where high activity is needed with human intervention mixed with a relatively dormant autonomous state the approach to fault torerance may be quite different than any one approach now studied.
Precedents	Fault tolerance has been investigated at JPL for over a generation with particular emphasis on the unmanned spacecraft application. Other investigators have also been concerned with just the hardware aspects in operations requiring very safe operation. Work is now being done at JPL looking at the reliability aspects of distributed systems with the functional software being redistributed as the hardware fails a piece at a time.
Technology Readiness	Breadboard testing of replacement type fault tolerant data systems microprocessors is now current. Military support for a program to incorporate a redundant operations monitor in a planned spacecraft is ongoing, Level 4.
Schedule	Based on current schedules qualified fault tolerant microprocessors for space application should be ready in 4 to 5 years.

Title: 5.G Radiation Hard Microprocessors

Description: Includes a microprocessor on a chip that is radiation hard and low power. The technology effort would be expected to be geared around developming a manufacturing process that would allow taking an integrated circuit mask of a proven microprocessor design, and fabricating it in a radiation hard version.

Rationale: Even though the Space Station may not be expected to encounter radiation environments, the need to have some electronic elements radiation hard is very likely. First of all the radiation requirements have not been firmly established for the SS, and secondly things could always change even after they are set. The main argument for radiation hard elements though is that there may be local radiation environments on board the SS, such as proximity to radioactive power generators, and electronic systems that include microprocessors could very likely be nearby.

Issues: A major issue surrounding the development of radiation hard microprocessors is with regard to the chip becoming obsolete by the time it is developed. For this reason, the pursuit of the technology should be geared toward developing manufacturing capability that could be applied to any proven LSI design, and not necessarily toward the qualification of an existing microprocessor.

Precedents: The development of radiation hard LSI and VLSI devices is one area of technology that private industry has not put much emphasis on. The reason is strictly economically, since there is not much of a market for these devices (other than the military and NASA) and they would rather concentrate on more profitable ventures such as development and sale of commercial microprocessors. Because of this situation, it falls pretty much on the military and NASA to fund the development of this technology. Fundamentally there are no known roadblocks other than identifying funding sources.

Title: 5.C Radiation Hard Microprocessors (Cont.)

Technology Readiness: There has been significant effort expended in this area both by the military and NASA with respect to a particulay device--the 1802 microprocessor for Galileo for example. The technology suggested herein in for the development of a manufacturing capability that would apply to any LSI or VLSI chip. That technology is probably currently at a level 4 or 5.

Schedule: Given a reasonable amount of resources, it would be expected that this technology could be brought up to a level 7 in time for the initial SS development.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title	5.H Flight Quality High Density Bulk Storage
Description	Storage media on board the station which contains additional or alternate progarams for data management use which can be evoked automatically.
Rationale	Ephimerides, reconfiguration strategies, and other archival data may be required on-board the station and the selection could be accomplished by ground command or autonomously. In either event, pre-stored data readily available would avoid the necessity of long ground command sequences to send the data. Reconfiguration may be required at an unplanned time in the autonomous mode.
Issues	Bulk storage is almost always accompanied by rotational media mechanically actuated. This is not a hinderance to acceptance as tape recorders have been used successfully for years in space. Adaptation of existing bulk storage means used in personal computers would require some means to select and load the media, comparable to a phonograph disc selector or jukebox.
Precedents	The bulk storage needs of all types of computational or imaging systems have driven the technology for this use. Commercial, military, and NASA space systems have all participated or directed the efforts.
Technology Readiness	Tape and disc magnetic storage technology is well in hand, but laser written disc storage appears to be a much denser approach now in the offing. Level 4-7, depending on approach.
Schedule	Qualified tape recorders now exist, but it would take 2 years or more for disc magnetic systems to be space qualified and 4 years or more for the laser discs.

Title	5.I System Executive/Data System Architecture
Description	Operating systems and executives peculiar to and adapted for distributed data systems with distributed software.
Rationale	The need for the executive software to operate autonomously as well as with human inputs and the concomitant need for the data system to reconfigure from the autonomous to attended mode poses new problems in these areas.
Issues	Development of this technology requires that all the other aspects of space station operation in the two modes be well understood and should naturally proceed apace with those studies. This a continually evolving field being a function of elemental architectures, command structures, protocols, and can only be studied in a general way until specifics are determined.
Precedents	These intertwined areas have been continually investigated since the advent of computers. This application is a substantial extension owing to the two modes of operation which up to now have been disparate.
Technology Readiness	The ongoing continual nature of software and architecture developments would indicate that most of the tools for extrapolating present methods now exist. The development hinges on defining the variables. Level 7.
Schedule	This type of development is essentially creative and is nearly always personnel intensive. Depending on the freeze dates of the various elements, two or more years would be required.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title	5.J Special Purpose Algorithm Development
Description	Algorithms for ground support, training, command generation, and other data system activities.
Rationale	This development activity is needed because of the advanced nature of the system and particularly because of the two different modes of operation of the system.
Issues	The issues involved in this development are primarily those of defining what it is that the system has to do and what information will it have to work on and when are the results needed and in what form are they desired.
Precedents	This is an area of development that is common to all data systems.
Technology Readiness	Algorithm development is fairly well understood and should pose no particularly difficulties as long as the issue items can be determined, Level 7.
Schedule	Algorithm development should be ready when needed.

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title	5.K Robotics/Teleoperators/A.I./Expert Systems
Rationale	The use of the this complex area of new technology on near term space stations is minimal if it exists at all, but systems farther in the future will probably rely on all of the aspects.
Issues	This area of research involves computer developments both in hardware and learning type software; sensors with a high degree of dynamic range and flexibility and tactile sense; and, mechanical actuators with many degrees of freedom and power gain.
Precedents	Work is centered commercially mainly in the sensor and actuator area for production line robots with the universities and other research areas studying the adaptive-learning programs, imaging algorithms, and fuzzy mathematics that accompany the research. Most of the current working systems exhibit a miniscule degree of the autonomy ultimately desired.
Technology Readiness	The state of the art is almost entirely in robots with the exception of a few toys or demonstration curiosities which serve to whet the sponsors appetite for more. Level 1-4, depending on application.
Schedule	???????

DATA MANAGEMENT SYSTEM TECHNOLOGIES

Title: 5.1 Automated Sequence/Command Generation

Description: Includes the capability to automate the process of developing flight sequences and command files. It would investigate automating both ground and onboard sequence/command generation capability.

Rationale: The sequence and command generation process consumes a signigicant amount of time and other resources. A first goal would be to automate portions of the activities that are currently done on the ground, and then expand into automating an onboard sequence and command generation capability. The objective would be to reduce both the time and the cost of performing this function.

Issues: There have always been ongoing arguments as to whether automating a process such as this or even moving it onboard is a worthwhile thing. Some claim that it will save resources, while others claim that it will not. It does have the potential of saving resources, and should be pursued until it can be proven one way or the other.

There is always the problem of coming up with general purpose capability rather than having it geared to a particular system. General capability should be the goal of this technology activity.

Precedents: Portions of the sequence and command generation process have been automated in the past on both deep space and earth orbital missions. Command translaters and specialized macro assemblers are examples.

Technology Readiness: A limited capability currently exists to automate the sequence and command generation process, and would have to be considered a level 7 on the technology readiness scale. The goal of the technology proposed herein is to improve on the current capability. We are presently at about a level 4 or 5 on the scale based on what is theoretically possible.

Schecule: Since this effort is geared toward improving an existing capability, a schedule is meaningful only after the goals are established. It is expected that a couple of years effort could yield improvements that could benefit the initial SS development phase.

Title: 5.M Automated Position/Time Generation

Description: Includes the development of systems that can be automatically interrogated to determine relative position and absolute time information. GPS type systems are examples of systems that can provide this capability.

Rationale: The rationale for including this as a technology area so far as the DMS is concerned would be that it makes it possible to improve some existing capability and automate functions that otherwise could not be automated. Examples include the onboard sequence and command generation capability that is a candidate for automation. There is no attempt being made herein to justify the overall technology area, but rather to point out how it would benefit the DMS if it were developed.

Issues: There is always the argument of whether or not there is any benefit to putting capability onboard if it can be done adequately on the ground. The calculation of position and time can be done on the ground, but if it were done automatically onboard it would make it possible to automate certain SS functions that could not otherwise be automated.

Precedents: There are both R/AD and ongoing programs within both NASA and the military that are pursuing this capability. The GPS system is an example.

Technology Readiness: The efforts currently ongoing in this area have carried the technology to a least a technology readiness level of 4 or 5.

Schedule: With the development programs currently underway, it is expected that the technology could be at a level 7 by the late 1980's.

Title	5.N Hardware Design Aids
Description	Computer aided design means for discrete circuitry, hybrids and integrated circuit mask generation geared in this application for input-output interfaces and intra data system use.
Rationale	An extension of existing technology may be needed in the data system are depending upon the degree of novelty of the architecture and mechanization of the system and the interfaces with the gatherers of data for autonomous operation.
Issues	The issues in this particular application are mainly determined by how different the implementation will be from what is available now or in the near future in circuitry, components, sensors, and actuators.
Precedents	Research and development has been addressed to this area for a long time starting with computer modelling of discrete devices and is now at the point where practically every major manufacturer offers some sort of integrated circuit design station.
Technology Readiness	Terminals exist for doing logical design of I-Cs at the engineer's desk. Computer programs for doing discrete design have proliferated to a high degree. Some modelling of new devices may be needed to incorporate the parameters into existing design aid programs.
Schedule	This area is at level 7 for state of the art hardware and appears to track the hardware developments closely.

ASST SPACE STATION FUNCTIONS-DATA MANAGEMENT

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
2.51200000	Accept maneuver parameters generated onboard and incorporate them into on orbit correction maneuvers	
2.51300000	Provide computational capability as required to perform orbit correction maneuvers	
4.51000000	Accept and decode commands from the ground	
4.51100000	Determine who the commands are meant for and route them to the appropiate element.	
4.51200000	Store "delayed commands in the DMS for later execution.	
4.51210000	Issue "delayed commands" at the appropiate time and to the appropiate element.	
4.52000000	Generate and issue commands derived from onboard conditions/algorithms	5k 5j
4.53000000	Monitor other SS elements for confirmation of receipt of commands.	
4.53100000	Provide capability to re-issue commands not acknowledged when sent first time.	
..54000000	Provide for "fall back" and recovery routines in the event of disrupted command sequences.	
4.55000000	Provide support to the ground operations systems as required to generate ground command sequences for storage onboard	5l 5j ab
6.51000000	Provide hardware data links and/or busses to any elements that must communicate with the DMS	
8.51000000	Provide computational capability to be compatible with any onboard capability for planning and generating sequences	5l 5j
8.52000000	Support ground activities by providing DMS expertise and simulation capability	5l 5j ab
9.51000000	Provide a precision oscillator as the central timing and synchronization source of the space station	
9.52000000	Provide a central clock (derived from the precision oscillator)	
9.52100000	Allow for adjustments/corrections either manual, automatic, or commanded (including interfacing with GPS type satellites)	5n
9.53000000	Distribute clock information to appropriate elements	
9.54000000	Provide reset/resynch capability for all onboard timing (power-On-reset capability)	
9.54000000	Provide required synchronized clock frequencies to appropriate users	
10.51000000	Provide data collection capability from all engineering subsystem	

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ASST SPACE STATION FUNCTIONS-DATA MANAGEMENT

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
10.51100000	Provide temporary storage capability for collected data	
10.51200000	Provide capability for formatting data as required	
10.52000000	Multiplex engineering data with other data and form it into a single data stream for downlink	
10.53000000	Provide capability for onboard monitoring and display of engineering measurements	
10.53100000	Distribute engineering data to other interested Space station elements as well as to the down link	
11.51000000	Provide data collection capability from all experiment (science and user) data sources	
11.51200000	Provide capability to format data as required	
11.52000000	Provide capability to add time and other header information to data as required	
1.53000000	Provide capability for multiplexing all data collected into a single data stream for downlink	
11.54000000	Provide capability for onboard monitoring and analyses of collected data	5k 5j ab
12.52000000	Provide computational capability to perform needed calculations based on collected data	
14.51000000	Provide computational capability for determining when a fault ocurrs (both inside and outside the DMS).	
14.51100000	Provide for collection of the required engineering data	
14.52000000	Provide computational capability for implementing fault management algorithms	
14.52000000	Provide computational capability for implementing fault management algorithms	
14.52100000	Provide means for altering fault management algorithms	
15.51000000	Provide for data collection to determine the status of space station elements	
15.52000000	Provide for computational capability to implement routine maintenance algorithms	
15.52100000	Compare the "conditions" with pre-determined criteria for what should be done.	
15.52200000	Provide means for altering routine maintenance algorithms	
15.52210000	Determine what alterations should be made in the algorithms	5j 5b
16.51000000	Provide data collection capability, computational capability, and commanding capability as required	

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ASST SPACE STATION FUNCTIONS-DATA MANAGEMENT

Area code 1=PROP 2=C&T 3=DPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
17.51000000	Provide data collection capability, computational capability, and commanding capability as required	
18.51000000	Provide computational capability for performing test and calibration of space station elements that do not contain this capability within themselves	
19.51000000	Provide override capability to automated features	
20.51000000	Provide both volatile and non-volatile data storage	5h 5d
20.52000000	Provide for both random access and serial access to storage media	
20.53000000	Provide both off-line and on-line storage	5h 5d
20.54000000	Provide both program and raw data storage	
20.55000000	Provide for manual access of the stored data as well as access via the DMS	
`.56000000	Provide for expandability of the data storage capability	
21.52000000	Provide computational capability as required	
22.51000000	Provide a modular, expandable DMS that allows for adding/subtracting elements as required	cf gi en
24.51000000	Provide for collection of required data	
24.51100000	Provide for onboard display of data as well as inclusion of the data in the telemetry stream	
24.52000000	Provide computational capability as required to interpret or process the collected data	
25.51000000	Provide capability for monitoring and commanding all elements of the space station that require executive control	5i
25.52000000	Provide computational cpability to process and interpret the collected data	5i 5j
25.53000000	Provide capability for altering executive control algorithms and associated programs	

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ASST SPACE STATION FUNCTIONS-DATA MANAGEMENT

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CODE
4.52000000	Generate and issue commands derived from onboard conditions/algorithms	5k 5j
4.55000000	Provide support to the ground operations systems as required to generate ground command sequences for storage onboard	5l 5j ab
8.51000000	Provide computational capability to be compatible with any onboard capability for planning and generating sequences	5l 5j
8.52000000	Support ground activities by providing DMS expertise and simulation capability	5l 5j ab
9.52100000	Allow for adjustments/corrections either manual, automatic, or commanded (including interfacing with GPS type satellites)	5n
11.54000000	Provide capability for onboard monitoring and analyses of collected data	5k 5j ab
15.52210000	Determine what alterations should be made in the algorithms	5j 5b
20.51000000	Provide both volatile and non-volatile data storage	5h 5d
20.53000000	Provide both off-line and on-line storage	5h 5d
22.51000000	Provide a modular, expandable DMS that allows for adding/subtracting elements as required	cf gi en
25.51000000	Provide capability for monitoring and commanding all elements of the space station that require executive control	5i
25.52000000	Provide computational cpability to process and interpret the collected data	5i 5j

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ATTITUDE CONTROL SYSTEM TECHNOLOGIES

7A Develop an interactive autonomous ACS with an interface to an autonomous NAV system on board the Space Station

* 7B Develop and interactive autonomous ACS with an interface to an autonomous Traffic Control system on board the Space Station

* 7C Flight qualify radiation tolerant computers and memories (both volatile and non-volatile)

* 7D Develop network or distributed system data distribution and executive control for Space Station application

* 7E Develop the architecture of and the interfaces among an autonomous ACS, a Space Station system executive, and the crew

* 7F Develop an integrated sensing and processing technique for in-flight system identification of Space Station dynamics, flexible body characteristics, and control performance

* 7G Develop Space Station distributed and adaptive control techniques for the suppression, decoupling, and isolation of dynamically interactive elements (e.g., modules, payloads, attached structures)

* 7H Develop an integrated precision pointing system for small payload control on the Space Station

* 7I Develop the sensing and integrated control technology for the crew and manipulators or teleoperators on board the Space Station

* 7J Develop the optical and inertial sensors, and effector technology for the support of attitude and pointing control

* 7K Develop an automatic command sequence generation capability

7L Develop Bite for ACS devices and the interface with autonomous fault protection and maintenance control

* 7M Develop the technology for autonomous adjustment of control laws, and an adaptive, supervisory fault management system

ATTITUDE CONTROL SYSTEM TECHNOLOGIES

ACS Autonomy Technology

Priority Ranking

Code	Title	Category	Ranking
7d:	Dist. data sys. & auto. ACS exec. control	A	1
7g:	Dist. & Adapt. Control	A	2
7f:	In flight system ID	A	3
7i:	Sensing & Effect. tech. for manip. & teleop.	B	4
7j:	Adv. Opt. & Iner. sens. & effect. tech. for att. & ptng.	B	5
7i:	Inter. Manip. & Teleop. with crew	B	6
7m:	Auto. adjst. & adap. ACS fault manag.	C	7
7h:	Integrated precision ptng.	C	8
7e:	Inter. auto. ACS, sys. exec.& crew	C	9
7l:	Auto. BITE for ACS devices	C	10
	Automatic command seq. generation	C	11
7a:	Inter. auto. ACS & NAV	AD	12
7b:	Inter. auto. ACS & Traff. Control	AD	13
7c:	Flight rad. hard mems. & CPU's	C	14

Category Legend:

- A - Technology development needed for any capability
- B - Technology development needed for extensive capability
- C - Technology development desirable but not critical
- D - Technology development applicable to far - term application onl
- E - Technology development need is undefined.
- AD - Advanced development not technology development
- NA - Not applicable for ACS technology development

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* 7A Develop an interactive autonomous ACS with an interface to an autonomous NAV system onboard the Space Station

DESCRIPTION: Interface would include data support for:

(ACS → NAV)
* A shared sensing system outputs
* Attitude state vector
* ACS configuration and health status information
* Attitude controller and performance parameters

(NAV → ACS)
* Maneuver configuration commands
* Maneuver initiation, execution, and termination commands

Justification: The development of such an ACS with an interface to an autonomous NAV supports the real-time performance constraints of autonomous orbit maintenance and near vicinity collision avoidance. Coupled with a system executive, support for crew maneuver control is provided.

Issues:
* Extent of real-time maneuver control exercised by NAV over ACS
* Number, use, and protection of shared sensors
* Design of ground/system executive/crew management /control of this interface

Precedents:
* ASP : AFMMS development

Technology Readiness: * Today: Basic Research and Development (Level 2-3)

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* 7B Develop an interactive autonomous ACS with an interface to an autonomous Traffic Control system on board the Space Station

Description: Interface would include data support for:

(ACS → Traffic Control)
* Shared sensor outputs
* Attitude state vector
* ACS configuration and health status information
* Attitude controller and performance parameters

(Traffic Control → ACS)
* Maneuver configuration commands for
    * Attitude bias / parameter values
    * Device configurations
* Maneuver initiation, execution, and termination commands

Justification: The development of such an ACS with an interface to an autonomous Traffic Control system supports the real-time performance constraints of autonomous rendezvous and docking, cooperative vehicle tracking and control, and near vicinity collision avoidance. This system reduces ground or crew dynamic workload.

Issues:
* Profile of real-time maneuver control of Traffic Control over ACS
* Number, use , and protection of shared sensors
* Design of ground/system executive/ crew management /control of this interface
* Profile for attitude control of berthed, docked, undocked vehicles

Precedents:
* Ground control systems: Air traffic control
* Apollo docking system

Technology Readiness: * Today: Basic Research and Development (Level 2)

153

* 7C **Flight qualify radiation tolerant computers and memories (both volatile and non-volatile)**

Description: Introduce radiation hardened, flight qualified memories on the Space Station and free flyers for non-volatile storage of:

- * command sequences and commanded data
- * back-up programming
- * audit trail
- * key parameters

and for volatile storage of

- * scratch pad data
- * random access data
- * programs

Also introduce radiation tolerant computers for the processing of ACS control laws and support functions; thus providing the protection from

- * software execution errors
- * CPU error transients

Justification: The introduction of such parts on a wide scale will reduce bit error rates and transient radiation induced effects, thus increasing computing system reliability.

Issues: * Requirements for introduction on the Space Station

* Power usage and performance capabilities

Precedents: * Bubble memory and Rad hard CMOS on Galileo

* ARMMS SCCM development

Technology Readiness: * Today: Advanced Development (Level 4)

* 7D Develop network or distributed system data distribution and executive control for Space Station application

Description: Develop the protocols for the distribution of commands and data among the ACS , ground station, crew and Space Station system executive. Utilize or adapt existing network and distributed system technology for the:

* distribution of commands and data to and from the ACS
* management of ACS processors and memories: computation and data flow
* management of ACS interfaces to ground/ crew/ system executive

Justification: The development of this data system and an executive control function supports the anticipated growth in computing capability in an evolving station concept. Computers may be added without redesign of the initial system. Hierarchical control supports overall system reliability and autonomy.

Issues:
* Architecture selection , which supports real-time ACS processing requirements
* Interface design, which supports command and data throughput constraints

Precedents:
* Ground based computer systems: ARPANET

Technology Readiness:
* Today: Basic Research and Development (Level 3)

155

* 7E Develop the architecture of and the interfaces among an autonomous ACS, a Space Station system executive and the crew

Description: Develop the architecture and interface which provides data and command support for:

- * system-wide distribution of data to and from the ACS, including crew interface data:
  - * Attitude state vector and ACS mode of operation
  - * ACS configuration and health status
  - * Attitude control and performance parameters
  - * Fault protection: alert and alarm indications
  - * Ground and system executive override control indications
- * executive control of fault recovery and routine maintenance of the ACS, including crew control for:
  - * Override of fault protection activities
  - * Initiation / override of routine maintenance
- * executive control and support of attitude and pointing control, including crew control for:
  - * Attitude bias
  - * Configuration changes
  - * Maneuver commands
  - * Parameter and programming changes
- * initiate ACS support of
  - * special environment control
  - * ground communications
  - * station and free flyer assembly and repair
  - * EVA activities

Justification: Development of such an architecture supports the anticipated growth in the function and sophistication of the attitude and pointing control systems of an evolving station. This architecture aids the reliable control by the crew of ACS modes and functions.

Issues:
* Architecture selection, which partitions executive duties among the ACS executive, system executive, crew
* Profile of crew and executive control capability over ACS functions
* Crew and system executive interface protection
* System executive / ground/ crew control priority and requirements

Precedents:
* Galileo: CCD/AACS interface design and functional partitioning
* " User - friendly" software systems

Technology Readiness:
* Today: Basic Research and Development (Level 3)

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* 7F Develop an integrated sensing and processing technique for in-flight system identification of Space Station dynamics, flexible body characteristics, and control performance

Description: Accept inputs from a variety of sensing sources and process data to compute the parameters of control of the

* initial station
* station with berthed or docked vehicles
* evolving station : modular growth
* payloads : both for integrated station attitude control and for position control of extended / flexible bodies
* manipulator control

during all modes of ACS operation. This system ID function must further be integrated with the fault management and autonomous maintenance of the sensing and processing hardware.

Justification: In-flight system identification establishes control performance, determines vehicle inertia and c.g. location, calibrates control parameters, and evaluates mode frequencies. This function removes the risk of control performance dependent on inaccurate pre-flight knowledge of vehicle dynamics, particularly for an evolving station.

Issues:
* Degree of implementation on the initial station
* Placement of sensing and actuating devices on the station structure
* Design of the parallel processing required for real-time application of system ID on board the station

Precedents:
* NASA OAST funded studies
* University based research

Technology Readiness: * Today: Basic Research and Development (Level 2-3)

158

* 7G Develop Space Station distributed and adaptive control techniques for the suppression, decoupling and isolation of dynamically interactive elements (e.g., modules, payloads, attached structure)

Description: Adapt distributed control technology to the Space Station for base motion isolation, controlled decoupling, active modal control, modal cancellation and frequency separation of disturbance sources. This control scheme will be utilized for the control of the

- * initial station flexible dynamics
- * station with berthed or docked vehicles
- * evolving station : modular growth
- * payloads : both for integrated station attitude control and for position / pointing control of flexible bodies
- * manipulator control

during all modes of ACS operation. Also, utilize adaptive control techniques for autonomous controller performance analysis and update. These techniques must be integrated with the fault management and autonomous maintenance of sensing, processing and effector hardware.

Justification: Distributed control techniques reduce structural weight and design constraints, associated with single-point control systems. Further actuation size and performance requirements are reduced and disturbance sources damped to allow an increased payload pointing capability. Adaptive control compensates for poorly known or changing control parameters.

Issues:
- * Degree of implementation on the initial station
- * Station growth constraints and design, including reboost support
- * Placement of sensing and effecting devices on the station structure
- * Payload disturbance isolation design
- * Design of parallel processing required for real-time application in the station ACS

Precedents:
- * NASA OAST funded studies
- * University based research

Technology Readiness: * Today: Basic Research and Development (Level 2)

159

* 711 Develop an integrated precision pointing system for small payload control on the Space Station

Description: Develop a package of sensing, effecting and processing for small (< 500kg) payloads which provides for :

* Precision pointing control
    * Precise position sensing
    * Precise control actuation
* Momentum compensation and disturbance isolation

In addition, introduce adaptive and distributed control techniques for autonomous pointing control at a specified level of performance.

Justification: The development of such a package provides precise, high tracking rate pointing control without excessive base body disturbance. This package offers benefit to the initial station dynamic disturbance control and payload support functions.

Issues:
* Selection of sensors and actuators
* Payload pointing requirements
* Station pointing and attitude control requirements

Precedents: * Galileo scan platform

Technology Readiness: * Today: Advanced Development (Level 4)

160

71 Develop the sensing and integrated control technology for the crew and manipulators/teleoperators on the Space Station

Description: Develop a sensing, data and command interface among the crew, system executive and manipulators/ teleoperators which provides support for:

* Remote sensing:
  * Machine vision
  * Proximity and force-torque / tactile sensing
* Integrated Control:
  * Disturbance damping
  * Coordinates: station, earth centered
  * Autonomous tracking during: autonomous berthing and docking, assembly EVA, payloads, TMS's, and OTV's
  * Commanding: automatic manipulation and teleoperation, autonomous tracking, payload support, and tethering/berthing/docking

Justification: Such sensing and integrated control provides for autonomous manipulator control, automatic tracking and automatic determination of objective attitude, and reduced dynamic disturbances. These features reduce astronaut burden in the use of manipulators and teleoperators.

Issues:
* Degree of autonomous operation / supervisory control
* Initial station application
* Human factors in design
* Motion / disturbance compensation requirements

Precedents:
* Shuttle arm
* Radioactive material handling

Technology Readiness:
* Today: Basic Research and Development (Level 3)

* 7J Develop the optical and inertial sensors and effector technology for the support of attitude and pointing control

<u>Description:</u> Develop the solid state, no moving parts, long-lived and 'smart' devices for application to sensing and controlling:

* Station reference in inertial space
* Station attitude
* Position of flexible structures and attached payloads
* Pointing of payloads

<u>Justification:</u> The development of such sensors, integrated with microprocessors and under computer control, reduce system processing requirements, provide modular units for growth in capability and increase performance and adaptiblity to payload and mission requirements.

<u>Issues:</u>
* Number, use and placement of sensors and effectors
* Pointing and control requirements of station and attached payloads

<u>Precedents:</u>
* OAST funded programs:
  * SHAPES, FORS, ASTROS
* Flight program advanced development programs
  * Microstepper harmonic drive actuator (HALLEY)
  * Magnetic bearings designed for momentum exchange devices
  * GPS receiver
* Flight qualified devices:
  * CMGs, reaction wheels, magnetic torquers
  * Accelerometers, gyros, DRIRU II, NASA standard: star tracker, sun sensor, earth limb (IR) scanner

<u>Technology Readiness:</u>
* Today: Basic Research and Development (Level 3)

161.

* 7K Develop an automatic sequence generation capability

Description: Develop the capability to generate command sequences in response to 'high-level' commands input from the ground/ system executive/ crew for:

- Automatic calibration of sensors and actuators
- Maneuver or traffic control
- ACS configuration or change of mode
- ACS parameter or programming updates
- Fault recovery or routine maintenance
- ACS self-test and validation
- ACS support for environment control
- ACS support for ground communications
- ACS and teleoperator support for service of OTV's and TMS's
- ACS and teleoperator support for payload deployment, pointing and control
- ACS and teleoperator support during station assembly
- Supervisory control of manipulators and teleoperators
- ACS and teleoperator support for EVA

Justification: The development of such a capability provides a reliable and 'user-friendly' method to command ACS devices and functions. This capability also reduces the sequence storage and ground manpower requirements to conduct mission or payload objectives, maintain station integrity, and manage station resource

Issues:
- Degree of development for the initial station
- Autonomous validation of command sequences

Precedents:
- Galileo scan platform control
- Voyager automatic science sequence generation

Technology Readiness: * Today: Basic Research and Development (Level 3)

163

* 7L Develop BITE for ACS devices and the interface with autonomous fault protection and maintenance control

Description: Develop and integrate built in test equipment (BITE) and test procedures into the design of the electronics for ACS devices and peripherals.

Justification: Such BITE designed equipment provide periodic and automatic self-test and configuration control. This relieves part of the fault management and autonomous maintenance software design responsibility for devices fault management by placing the fault detection and correction logic at the lowest possible level of control. The fault management software must respond to BITE reports in case of fault recovery or mode sequencing—actions with system-wide impact.

Issues:
* Requirements for BITE in equipment on board the Space Station
* Fault management and autonomous maintenance software support and adaptation to devices designed with BITE.

Precedents:

Technology Readiness: * Today: Basic Research and Development (Level 2-3)

164

* 7M Develop the technology for autonomous adjustment of control laws, and an adaptive, supervisory fault management system

Description: Develop for Space Station application expert systems which adjust control laws based on pointing and control performance analysis. Such systems may also allow for optimizing maintenance and fault management of ACS devices and peripherals. An expert system would provide parameter and programming updates.

Justification: The development of such systems, which learn and apply space system judgements, reduce the requirements for sophisticated, multi-scenario fault management or autonomous adjustment test and validation. Such systems provide growth adaptibility for evolving station concepts.

Issues:
* Requirements for Space Station application:
  * On board implementation
  * Ground support of station operation
* Expert system / artificial intelligence technology maturity

Precedents:

Technology Readiness: * Today: Basic Research and Development (Level 1-2)

ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
1.71000000	Acquire solar reference	
1.72000000	Provide intra-subsystem conditioning and distribution of power	
1.73000000	Point to maintain solar array normal to the sun line	
2.71000000	Provide data to NAV for manuever planning and performance	7a
2.72000000	Provide attitude control during maneuver	7a
2.73000000	Respond to NAV/ ground/ system/crew/ generated commands to execute/abort manuevers	7k
2.74000000	Provide attitude bias for optimal orbit change	7a
2.75000000	Perform routine maintenance to minimize drift in on-orbit position	
2.76000000	Provide data for tuning of c.g., atmospheric drag, and solar pressure models	7a
3.71000000	Provide data to NAV for free flyer traffic control and formation flying	7b
3.72000000	Provide attitude control or biased attitude during traffic control/formation flying	7b
3.73000000	Respond to NAV/ ground/ system/ crew generated commands	7b 7k
4.71000000	Receive ground/crew/system/ generated commands	7e
4.72100000	Provide non-volatile storage of key parameters, uplinked command sequnces (maneuver, calibrations, special contigencies, etc.)	7c
4.72200000	Reload/ back store programming	7c
4.73100000	Provide commands to reconfigure G&C in fault recovery scenarios	7k
4.73210000	Provide for G&C mode sequencing	
4.73220000	Provide for parameter updates	
4.73230000	Provide programming updates	7m
4.73241000	Actuators: Momentum management, calibrations	
4.73242000	Sensors: calibrations	
4.73243000	Processors	
4.73244000	Structure alignments/active modal damping	
4.73250000	Provide command/data link test	

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL
Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV
Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
4.73260000	Provide G&C self-test and validation	
4.73300000	Provide high level command interpretation	7k
4.74000000	Distribute commands	7d
5.71000000	Respond to ground/system/crew generated commands	7k
5.71100000	Bias attitude for thermal control	7e
5.72000000	Compensate attitude for disposal/jettisoning of contaminants	
6.71000000	Provide attitude bias and antenna pointing to support communications	7e
7.71000000	Initial station deployment, implacement, and assembly mode	7e
7.72100000	Reduce RCS rates/deadbands	
7.72200000	Orient attached bodies (e.g., solar panels, radiators, antennae,etc.)	
7.72300000	Perform initial system ID	7f
7.72400000	Compute controller parameters	7f
7.72500000	Reference search/acquisition	7j
7.72600000	Transfer to momentum control system (e.g., CMG's, reaction wheels,etc.)	7j
7.73100000	Sense/determine/control attitude to final precision	
7.73200000	Perform adaptive control/parameter computation	7h
7.73300000	Control flexible dynamics	7g
7.73400000	Perform eclipse/occlusion attitude control	
7.74100000	Configure for maneuver	7a
7.74200000	Sense/determine/control attitude during maneuver (RCS and momentum control)	
7.74400000	Reconfigure for normal on-orbit mode	
7.75100000	Perform cooperative vehicle relative motion control	7b
7.75400000	Establish "old" control parameters upon undocking	
7.75500000	Reconfigure for normal on-orbit mode	

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
7.76100000	Sense/determine/control attitude	
7.76200000	Establish reduced attitude constraints during assembly	7g
7.76300000	Reconfigure/reestablish normal on-orbit mode	7g
7.77100000	Perform relative motion control for payload deploy/experiment/retrieve	7i
7.77200000	Respond to traffic control/ground/system executive/crew commands	7i
7.78100000	Perform attitude bias/introduce rates for sensor/actuator calibration	
7.78200000	Dump or acquire momentum	
7.78300000	Test & validate devices and functions	
7.78500000	Interpret high level commands	7k
7.78400000	Vent/compensate for expendables/consumables	
9.71000000	Provide subsystem cycle time (CPU) or rate group time	
9.72000000	Receive/synchronize to NAV or system master time (on-orbit time)	
9.73000000	Accept telemetry timing from telemetry and command subsystem	
9.74000000	Synchronize for command receipt	
10.71000000	Format or encode telemetry	
10.72000000	Provide hardware analog signals and bilevels	
10.73000000	Provide for audit trail (all or part)	
10.74000000	Provide for memory readout (all or part)	
10.75000000	Provide data for system-wide use (other subsystems, crew)	7e
11.71000000	Point/control antennae to receive user data	xx
11.72000000	Point/control user payloads [19.72000000]	
11.74000000	Safe user payloads/data communications during fault induced attitude anomalies	7k
13.71100000	Minimize thruster usage	
13.71200000	Balance CMG or reaction wheel momentum distribution	

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CODE
13.72100000	Manage processing use within ACS	7d
13.73100000	Manage non-volatile memory for	
13.74000000	Minimize power usuage	
14.71000000	Perform redundancy management	7e
14.72100000	Sensors	71 7e
14.72200000	Actuators	71 7e
14.72300000	Processing	7e 7c
14.72400000	Interfaces	7d 7e 7k
14.73000000	Perform fault protection/controller management	7f 7g
15.71000000	Mode sequencing	7e
15.72100000	Perform mission phase depedent parameter updates	7m
15.72200000	Controller performance analysis	7g
15.72300000	Accept ground/system/crew overrides	
15.73100000	Actuators	7k
15.73200000	Sensors	7k
15.73300000	Processors	
15.73400000	Structure	7g
15.74000000	Visibility and commandability	
15.76000000	Self-test and validation	
15.77000000	Provide programming updates	7m
19.71100000	Perform special payload control	7k 7i
19.71200000	Perform system ID [7.77000000, 7.72300000]	
19.72110000	Position sensing/shape sensing	7d eh j
..,72120000	Pointing error sensing	7j

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
19.72200000	Process	7d 7e
19.72310000	Execute actuator control commands	7j
19.72320000	Perform momentum compensation	
19.74000000	Perform dynamic disturbance decoupling and control	7g
20.72100000	Store and retrieve random access/scratch-pad data	7c
20.72200000	Store programs	7c
23.71100000	Checkout/deploy/assemble/adjust payloads	7i
23.71200000	Retrieve payloads	7i 7b
23.71300000	Install payloads in the shuttle	7i 7b
3.73100000	Operate manipulators for tethering/berthing	7i
23.73200000	Operate manipulators for auto docking	7i 7b 7e
23.74000000	Support the operation of TMS's	7i 7b 7e
23.75100000	Provide emergency retrieval	7i
23.75200000	Provide remote sensing	7i
24.71000000	Perform attitude control during EVA	7e
24.72000000	Perform attitude bias	7e
24.73000000	Respond to crew/ground/system/commands for attitude or pointing control	7e

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV
Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CODE
2.71000000	Provide data to NAV for manuever planning and performance	7a
2.72000000	Provide attitude control during maneuver	7a
2.73000000	Respond to NAV/ ground/ system/crew/ generated commands to execute/abort manuevers	7k
2.74000000	Provide attitude bias for optimal orbit change	7a
2.76000000	Provide data for tuning of c.g., atmospheric drag, and solar pressure models	7a
3.71000000	Provide data to NAV for free flyer traffic control and formation flying	7b
3.72000000	Provide attitude control or biased attitude during traffic control/formation flying	7b
3.73000000	Respond to NAV/ ground/ system/ crew generated commands	7b 7k
4.72100000	Provide non-volatile storage of key parameters, uplinked command sequnces (maneuver, calibrations, special contigencies, etc.)	7c
.72200000	Reload/ back store programming	7c
4.73100000	Provide commands to reconfigure G&C in fault recovery scenarios	7k
4.73230000	Provide programming updates	7m
4.73300000	Provide high level command interpretation	7k
4.74000000	Distribute commands	7d
5.71000000	Respond to ground/system/crew generated commands	7k
5.71100000	Bias attitude for thermal control	7e
6.71000000	Provide attitude bias and antenna pointing to support communications	7e
7.71000000	Initial station deployment, implacement, and assembly mode	7e
7.72300000	Perform initial systen ID	7f
7.72400000	Compute controller parameters	7f
7.72500000	Reference search/acquisition	7j
7.72600000	Transfer to momentum control systen (e.g., CMG's, reaction wheels,etc.)	7j
73200000	Perform adaptive control/parameter computation	7h
7.73300000	Control flexible dynamics	7g

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CODE
7.74100000	Configure for maneuver	7a
7.75100000	Perform cooperative vehicle relative motion control	7b
7.76200000	Establish reduced attitude constraints during assembly	7g
7.76300000	Reconfigure/reestablish normal on-orbit mode	7g
7.77100000	Perform relative motion control for payload deploy/experiment/retrieve	7i
7.77200000	Respond to traffic control/ground/system executive/crew commands	7i
7.78500000	Interpret high level commands	7k
10.75000000	Provide data for system-wide use (other subsystems, crew)	7e
11.71000000	Point/control antennae to receive user data	xx
'.74000000	Safe user payloads/data communications during fault induced attitude anomalies	7k
13.72100000	Manage processing use within ACS	7d
14.71000000	Perform redundancy management	7e
14.72100000	Sensors	7l 7e
14.72200000	Actuators	7l 7e
14.72300000	Processing	7e 7c
14.72400000	Interfaces	7d 7e 7k
14.73000000	Perform fault protection/controller management	7f 7g
15.71000000	Mode sequencing	7e
15.72100000	Perform mission phase depedent parameter updates	7m
15.72200000	Controller performance analysis	7g
15.73100000	Actuators	7k
15.73200000	Sensors	7k
15.73400000	Structure	7g
15.77000000	Provide programming updates	7m

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ASST SPACE STATION FUNCTIONS-ATTITUDE CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CO DE
19.71100000	Perform special payload control	7k 7i
19.72110000	Position sensing/shape sensing	7d eh j
19.72120000	Pointing error sensing	7j
19.72200000	Process	7d 7e
19.72310000	Execute actuator control commands	7j
19.74000000	Perform dynamic disturbance decoupling and control	7g
20.72100000	Store and retrieve random access/scratch-pad data	7c
20.72200000	Store programs	7c
23.71100000	Checkout/deploy/assemble/adjust payloads	7i
.71200000	Retrieve payloads	7i 7b
23.71300000	Install payloads in the shuttle	7i 7b
23.72100000	Assemble station modules	7i
23.72200000	Assemble/adjust free flyer/modules	7i
23.72300000	Replace station modules	7f 7i
23.73100000	Operate manipulators for tethering/berthing	7i
23.73200000	Operate manipulators for auto docking	7i 7b 7e
23.74000000	Support the operation of TMS's	7i 7b 7e
23.75100000	Provide emergency retrieval	7i
23.75200000	Provide remote sensing	7i
24.71000000	Perform attitude control during EVA	7e
24.72000000	Perform attitude bias	7e
24.73000000	Respond to crew/ground/system/commands for attitude or pointing control	7e

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THERMAL CONTROL SYSTEM TECHNOLOGIES

8A Develop an interactive, autonomous thermal control subsystem.

8B Develop an enviornment sensing pointable radiator system.

8C Develop onboard trend analysis and performance prediction capability.

THERMAL CONTROL SYSTEM TECHNOLOGIES

Code	Title	Category	Ranking
8A	Autonomous TC Architecture and Interfaces	AD	1
8B	Environmental Sensing Radiator	B	2
8C	Onboard TC Trend Analysis	D	3

Category Legend:

A - Technology development needed for any capability.

B - Technology development needed for extensive capability

C - Technology development desirable but not critical.

D - Technology development applicable to far-term application only.

E - Technology development need is undefined.

AD - Advanced development not technology development.

NA - Not applicable for TC technology development.

THERMAL CONTROL SYSTEM TECHNOLOGIES

8A Develop an interactive, autonomous thermal control subsystem.

Description

Develop the architecture and interfaces among an autonomous space station TCS, a space station system executive, other susystems and the crew, which provide data and command support for:

- Temperature monitoring
- Monitoring of TCS equipment status
- Thermal acquisition and transport
- Heat rejection
- Thermal utility integration
- Fault management
- Routine maintenance

Rationale

In the large and thermally complex space station system, autonomous space station-wide TC will significantly improve system reliability and operability while greatly reducing the probability of errors which lead to TC failures (which may propagate into larger system failures). Development of an adaptable autonomous TCS supports the anticipated growth in the function and sophistication of the TCS of an evolving station.

Issues

- Architecture selection including partitioning of executive duties among the TCS executive, the system executive, and crew.

- Determine priorities among the TCS executive, system executive, ground, and crew.

- Interface with power subsystem.

- Level of crew involvement with routine maintenance functions.

Precedents

- STS active thermal control subsystem.

- Galileo electronically controlled thermostatic heaters.

Technology Readiness Level

- Level of current technology: Basic Research and Development (Level 1-2).

8B) Develop an environment sensing pointable radiator system

Description:

Develop an environment sensing and control system to control the pointing of large heat rejection radiators on the space station. The following tasks are included in this development:

- o Determine size and mass savings relative to a final radiator system.
- o Determine sensor and mechanical actuator requirements
- o Assessment of available sensors for incorporation into an active environment sensing system
- o Determine maximum movement and rate requirements
- o Develop the control logic and actuator requirements for the system

Rationale:

The size and mass of the large radiators required for rejecting energy from the space station may be reduced by at least 40% over that of a fixed orientation radiator with the development of an autonomous environment sensing pointable radiator system. (See Space Station Systems Definition, Book 5, Section 6.5.) The environment sensors combined with control logic and mechanical actuators will continuously point the radiator towards the coldest region of space.

Issues:

- o Effect of radiator motion on space station
- o Integration and interface with the TCS executive

Precedents:

- o Existing environment sensors

Technology Readiness Level:

- o Level of current technology: Basic Research and Development (Level 1-2)

8C) Develop onboard trend analysis and performance prediction capability

Description:

Develop onboard trend analysis and thermal performance prediction capability. This is primarily a software development task.

Rationale

Automating trend analysis and performance prediction will reduce the work hours required for ground operations. Automating these functions onboard the space station may yield early warning of imminent hardware failures in areas other than thermal control (See Space Station Program Description Document, Book 3, Section 2.6.5. (a) and Book 5, Section 6.5.5)

Issues:

- o Interface with TCS executive

Precedents:

Manually performed ground trend analysis and performance prediction.

Technology Readiness Level:

- o Level of current technology: Basic Research (Level 1-2)

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ASST SPACE STATION FUNCTIONS-THERMAL CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=systen function second digit=area third and following digits=function level

NUMBER	FUNCTION THAT ARE CANDIDATES FOR AUTOMATION	CO DE
5.81100000	Spacestation-wide thermal control (including main body, appendages,and free flyers)	8a
5.81111000	Thermal acquisition and transport	8a
5.81111512	Provide control of heat pipes (passive, variable conductance, and diode)	
5.81111513	Monitor contamination on multilayer insulation (MLI) at critical locations	
5.81111514	Control contamination on multilayer insulation (MLI) at critical locations	
5.81111530	Control of fluid loop and components	8a
5.81112000	Heat rejection	8a
5.81112100	Provide pointing control of radiators	8b
5.81112210	Provide control of louvres	
5.81120000	Thermal utility integration (TC executive)	8a
5.81200000	Support of operations (trend analyses and performance predictions)	8c
5.82000000	Control contamination	
5.82100000	Monitor contamination	
5.82200000	Provide contamination data to other subsystems	
5.82300000	Provide capability to reduce contamination on critical surfaces (e.g. Optics, windows, radiators, etc.)	
5.83000000	Atmospheric control	
5.83130000	Airlocks	

ASST SPACE STATION FUNCTIONS-THERMAL CONTROL

Area code 1=PROP 2=C&T 3=OPS 4=EPS 5=DMS 7=G&C 8=TC 9=NAV

Number Code first digit=system function second digit=area third and following digits=function level

NUMBER	FUNCTIONS THAT REQUIRE OR BENEFIT FROM NEW TECHNOLOGY	CODE
5.81100000	Spacestation-wide thermal control (including main body, appendages, and free flyers)	8a
5.81111000	Thermal acquisition and transport	8a
5.81111530	Control of fluid loop and components	8a
5.81112000	Heat rejection	8a
5.81112100	Provide pointing control of radiators	8b
5.81120000	Thermal utility integration (TC executive)	8a
5.81200000	Support of operations [trend analyses and performance predictions]	8c
5.82000000	Control contamination	
5.82100000	Monitor contamination	
5.82200000	Provide contamination data to other subsystems	
5.82300000	Provide capability to reduce contamination on critical surfaces (e.g. Optics, windows, radiators, etc.)	
5.83000000	Atmospheric control	
5.83130000	Airlocks	

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NAVIGATION SYSTEM TECHNOLOGIES

Code	Title	Category	Ranking
9A	Onboard Navigation	A	1
9B	Navigation Crew Interactive System	A	2

Category Legend:

A - Technology development needed for any capability.

B - Technology development needed for extensive capability

C - Technology development desirable but not critical.

D - Technology development applicable to far-term application only.

E - Technology development need is undefined.

AD - Advanced development not technology development.

NA - Not applicable for NAV technology development.

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NAVIGATION SYSTEM TECHNOLOGIES

9A Develop an autonomous navigation system for establishing the Space Station orbit and maintaining the orbit in the presence of atmospheric and other disturbances.

Description

The orbit navigation system provides autonomous onboard navigation, requiring little interaction with the crew or ground systems. Its functions include acquiring orbit-related measurement data, processing these data to determine the Space Station orbit, acquiring orbit specifications from the astronaut or from ground systems, computing maneuvers to correct the orbit, and computing and issuing the corresponding maneuver commands.

Issues

- What navigation measurement sources to select: GPS or TDRS satellite data, onboard sensors for backup.
- The degree of automation versus crew intervention.
- Abort monitoring and response to detected failures.
- Access to GPS codes.
- Programming language.

Precedents

- Apollo
- Space Shuttle

Technology Readiness

Today: Level 1.

NAVIGATION SYSTEM TECHNOLOGIES

9B Develop a crew-interactive navigation system to monitor and control the orbits of free-flying vehicles which interact with the Space Station.

Description

The traffic control navigation system provides for the control of relative motion, including terminal rendezvous and stationkeeping, and for docking/berthing of the Shuttle and free-flying vehicles with the Space Station. ("Terminal rendezvous" is the relative motion of a free-flyer up to, but not including, docking or berthing). This highly crew-interactive system provdes primary intervehicular control functions for those free-flyers which have no intervehicular control facilities of their own, and backup functions for self-contained vehicles. Free-flyers include science platforms, OTVs, and ultimately OMVs.

Issues

- Whether there should be a ferry vehicle for parking and retrieving free-flyers.
- How the orbits are to be maintained to provide safe separation between free-flyers if they rely on a ferry vehicle and have no propulsion of their own.
- The division of responsibility between the Space Station and the individual free-flyers for determining and controlling their relative trajectories.

Precedents

- None.

Technology Readiness

- Today: Level 1.

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